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SUBSURFACE WARFARE

THE HISTORY OF DIVISION 6 NATIONAL DEFENSE RESEARCH COMMITTEE

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SUBSURFACE WARFARE

THE HISTORY OF DIVISION 6, NDRC

by

JOHN HERRICK

DATA LIBRARY
Woods Hole Oceanographic Institution

Prepared Under the Direction of

John T. Tate

Chief, Division 6, NDRC (1942-1946)

1 JANUARY 1951

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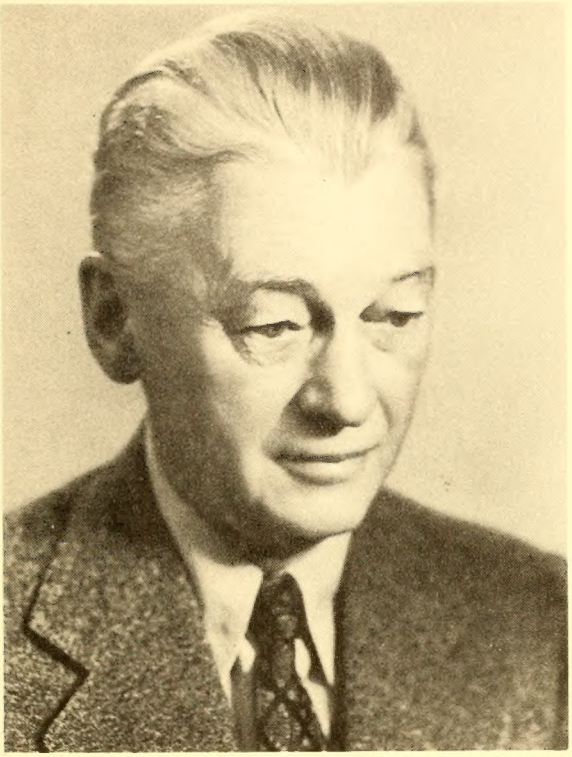
Washington 25, D. C.

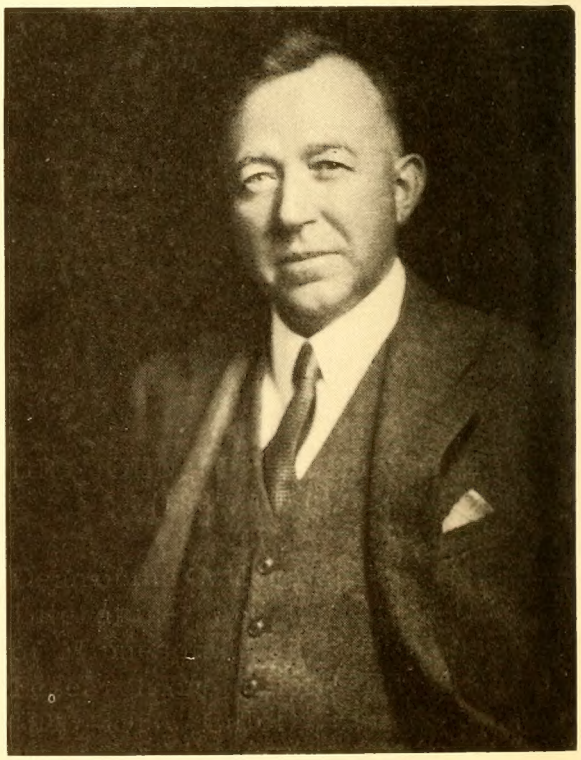


DR. JOHN TORRANCE TATE
(1889-1950)

Dean of the College of Science, Literature, and the Arts, U. of Minnesota 1937 - 1943, and Research Professor of Physics 1943-1950. Chief, Division 6, (Subsurface Warfare) NDRC; scientific advisor to the Commander-in-Chief, U.S. Fleet; deputy chief of the Office of Field Services of the OSRD in charge of Operations Research and chief and member of the Rocket Ordnance Division of the NDRC. 1940-1946. Awarded the Presidential Medal for Merit in April 1947.

DR. EDWIN H. COLPITTS
(1872-1949)

Vice - President, Bell Telephone Laboratories (Ret. 1937); Chairman, special subcommittee for U.S. submarine defense, National Academy of Sciences, 1940; Chief Section 6.1, NDRC; 1941-1946. Awarded the Presidential Medal for Merit on April 5, 1948.



FOREWORD

This narrative report of the activities of Division 6 of the National Defense Research Committee will recall many memories to those who spent their World War II years in the cooperative effort that constituted the Division's contribution to the defense of our nation. That this contribution was effective is due in major part to the deep and sympathetic understanding of the problems of nature and men which identified the wise leadership of the Division's Chief, John Tate. In carrying out his important undertaking, Dr. Tate was fortunate in having as his able deputy, Edwin Colpitts, who returned from retirement to carry much of the burden of organizing, guiding, and administering the details of a fifty million dollar program employing many hundreds of scientists of diverse interests and temperaments and extending over the entire United States and all theaters of Naval combat. Both Dr. Tate and Dr. Colpitts earned the gratitude of the Nation and the personal affection and respect of all who were privileged to be their associates.

In the years succeeding the disbanding of Division 6 in 1945, an effort has been made to keep alive the close contact and mutual understanding established during the past between the Navy and civilian scientists interested in the many difficult technical and operational problems characterizing modern antisubmarine warfare. And although long-delayed, perhaps the appearance of this report of a fruitful partnership is timely in this troubled period to remind us of the accomplishments possible in a spirit of common purpose.

GAYLORD P. HARNWELL

The Committee on Undersea Warfare
(Member, Division 6, NDRC)

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CHAPTER I

INTRODUCTION

Importance of Subsurface Warfare.

Twice in two World Wars the submarines of an aggressive enemy brought the United States and her allies to the brink of defeat.

In both World War I and World War II, the Allies succeeded only by the narrowest of margins in maintaining their vital lines of supply by sea.

During the approximately 51 months of World War I, enemy submarines sank some 4,837 merchant vessels, totaling 11, 135,000 gross tons. During the approximately 72 months of World War II, enemy submarines sank 2,753 merchant vessels, totaling 14, 557,000 gross tons, a total for the two wars of 7,590 ships of 25,692,000 gross tons -- not to mention the lives lost by thousands of brave seamen.

The battle of the Atlantic was the decisive battle of the antisubmarine war. The Germans might win the war if they produced the first atomic bomb. They had it won already unless their submarines could be destroyed.

As they had done during the first World War, the U-boats in 1939 and 1940 again struck savagely at the Allied shipping lanes to Great Britain. And the Nazi U-boat of World War II was a far more deadly weapon than its predecessor. It had greater range, greater speed, greater underwater endurance, a stronger hull, better armament and equipment. It was a surface raider with the power to submerge and attack from hiding, or to escape beneath the surface if confronted by a stronger foe. Nor could the U-boats be hemmed in, as in the first World War, by mine barrages in the Dover Straits and North Sea. Following the fall of the Netherlands, Belgium, and France, and the occupation of Norway, the U-boats could use bases situated along Europe's entire western coast line.

It is a noteworthy tribute to the Allied antisubmarine forces that the record shows that they fought even more effectively in the second U-boat war than they had in the first.

Estimates of Allied sinkings of U-boats in World War I totaled 178 or 3.5 per month. In World War II, the Allies destroyed a total of 783 enemy submarines according to Allied estimates, or 846 in all if enemy lists of losses are accepted -- a monthly rate of 10.8 on the basis of Allied figures, or 11.8 according to enemy summaries.

As in World War I, it was the ever-increasing U-boat offensive which made even more imminent our own involvement in the conflict. It gave unmistakable warning of the task which would face our Navy immediately, and against full enemy strength, on the day war was declared. Our Army might shun battle until it had been built up to strength. Our Navy could have no such choice. The enemy was poised, ready to strike, and would strike not only our trans-Atlantic and Pacific shipping, but also our coastal, South American and Gulf traffic, right up to our home harbors. Of what avail to build up an Army of 8 million men if the battle against the U-boat were lost?

How ready was our Navy to join battle with the U-boat? How well organized was the scientific and technical talent of the country to stand beside the Navy and engage in the inevitable battle of wits, of measure and counter-measure, with the scientific talent of the enemy?

These were the questions facing the Navy and the National Defense Research Committee when the latter came into being in June, 1940. The answers were not readily found.

Scope of This Volume

The present volume tells the story of part of the organization which NDRC established in April, 1941. It is the story of Division 6 (originally Section C-4) of NDRC, the sub-surface warfare division, which helped fight the U-boat and, when victory over the U-boat was assured, went on to assist our own submarines in the battle of the Pacific.

The history, the principal activities and some of the accomplishments of the Division will be recounted in succeeding chapters. The story cannot be complete because many of the most important developments are still held secret, so carefully guarded that the enemy does not yet know all that hit him.

It must be emphasized, too, that this is the story of only one of many research and development agencies, both in this

country and in Great Britain, whose cooperative effort resulted in the defeat of the U-boat. Notable among these were the two great U. S. Navy laboratories -- the Naval Research Laboratory of the Bureau of Ships and the Naval Ordnance Laboratory of the Bureau of Ordnance, and in Great Britain the Anti-Submarine Experimental Establishment of the Admiralty. The part played by our industrial research laboratories cannot be overemphasized; not only did they originate many new ideas, but they made the important contribution of reducing to manufacturable form the laboratory developments initiated by others. Other divisions of NDRC also contributed to the success of the anti-U-boat campaign. Most notable perhaps were the developments of Division 3 in rocket ordnance and of Division 14 in microwave radar. If, therefore, the present volume appears to lack balance in terms of the total Allied effort, it is because it is intended to be the story of but one aspect of that effort.

This volume is a record of achievement. Yet, lest this achievement lead to undue optimism, this introduction must end on a note of warning. It must be remembered that the U-boat at the end of World War II was not defeated. It had been driven to the defensive, but not from the seas. German submarines with their Schnorchel equipment were able to operate as true undersea craft rather than as submersible torpedo boats. Japanese submarines were preparing to attempt operations as submersible aircraft carriers. New types of Nazi U-boats capable of submerged speeds which might have made current Allied anti-submarine gear and tactics obsolete, were on the point of entering active service when the war ended. Had the Nazis been able to advance by even six months the operational use of these new-type submarines, the victory might well have been materially delayed and made far more costly.

CHAPTER II

SUBMARINE DETECTION PRIOR TO 1940

The Kaiser's admirals, at the outbreak of World War I, had in their submarines a better weapon than they realized, and one which an unprepared Allied technology was not ready to combat.

The U-boat successes of World War I are material to the story of sub-surface warfare during World War II because they set in train a scientific program to devise countermeasures, and because -- as has proved true in other fields of military unpreparedness -- the counter-measures which resulted came too late to play a major role in the war which generated them, but were to be the basis for the technical equipment of World War II.

Subsurface Warfare in World War I.

Though the Germans were able to keep at sea at any one time during 1915 and 1916, an average of only some 15 U-boats, their submarines, thanks in part to the British refusal to adopt the convoy system, sank an average of approximately 200,000 gross tons of Allied shipping per month.

Losses of U-boats averaged only $1\frac{1}{2}$ vessels per month. Thus, the life of a U-boat approximated ten months, during which it might be expected to sink 130,000 gross tons of shipping -- a fair bargain of war from the Germans' viewpoint and one which led them, in February, 1917, to commence a campaign of unrestricted submarine warfare.

Allied shipping losses from submarines rose steadily until, in April, 1917, they reached a peak of 440 ships totaling approximately 900,000 gross tons. This crisis, plus the insistent advice of America's Sims and Britain's Jellicoe, finally impelled the adoption of the convoy system.

But convoying, while it cut shipping losses, did not defeat the U-boat. From early in 1917 until the close of the war, the

Germans succeeded in maintaining an average of some 40 submarines at sea at all times. Allied losses, though far below the April, 1917, peak, still averaged approximately 300,000 gross tons per month. And U-boat losses were only some 7 per month.

Of the 178 U-boats sunk during World War I, only 45 per cent were sunk by surface craft. Thirty per cent were sunk by mines, 10 per cent by Allied submarines and the remaining 15 per cent were lost through other causes.

It was clear that though the Allies might make the U-boat a weapon hazardous to its user, they still had failed to make its employment a military extravagance. They had yet to develop a satisfactory means of detecting and tracking a submarine while submerged, and an offensive arm lethal against a U-boat below the surface.

For anti-submarine ordnance the Allies had the depth charge, but the "ash can" was a crude weapon. It could not be fired forwarded from the pursuing vessel. The depth setting of its fuze was largely a matter of guess work. Large patterns of great numbers of charges had to be dropped in order to achieve any chance of a kill. The greatest merit of the depth charge was the damaging effect of its blast on the morale of submarine crews.

To counter the U-boat menace effectively, some means of underwater detection had to be found and developed.

In 1917 the Submarine Signal Company set up a test station and laboratories at Nahant, Massachusetts, to which the Western Electric Company and General Electric Company sent a number of their top ranking scientists to work in a great co-operative endeavor. A few months later the Navy set up the U. S. Naval Experimental Station at New London, Connecticut. This station was staffed with scientists drawn from universities throughout the country.

Early Listening Devices.

Perhaps the first significant achievement of science in devising counter-measures against the German submarine was the development of devices for picking up and determining the direction of underwater sounds. One method was to use the binaural effect by which in ordinary listening, people determine

the direction from which sounds arrive at their ears. Determination of direction through the binaural sense involved the use of a dual listening system whether composed of simple acoustic tubes or passages or, as later developed, of electrical devices and amplifiers. It also required the exercise of judgment by the operator as to the apparent location of the sound he heard.

A second system of determining direction developed during World War I was the MV (later called the multi-spot) array, consisting of several receivers so connected that the signals picked up by each would combine cumulatively only when the sound came from a designated direction. Sounds could be received from an enemy submarine to the partial exclusion of the extraneous noises originating in other directions. This principle was of trememdous value in increasing the range at which sounds could be heard.

Beginnings of Echo-Ranging.

The multi-spot listening systems could detect a submarine, but indicated only its direction and there was no way of determining the range from a single listening station. It was not until 1918 that the British set up a committee known as the Allied Submarine Devices Investigation Committee (ASDIC) composed of Naval experts and scientists of the Allied countries. It was largely through the work of this committee that attention was directed toward the determination of the range of a sound source by echo-ranging.

Reduced to simplest terms, echo-ranging consists of using an underwater sound projector to send out a sound beam and of using an underwater sound receiver to listen for the echo sent back when the outgoing sound strikes a reflecting surface.

Experiments with sub-surface echo-ranging had been conducted as early as 1914, when the Submarine Signal Company, using Fessenden oscillators, had obtained echoes from the sea bottom and from the submerged portions of icebergs. Perhaps the first echoes ever received from a submerged submarine were observed by Boyle and his co-workers in England in 1918, using a quartz oscillator developed as the result of pioneering work in piezoelectric research by the French physicist, Langevin. By use of the Langevin oscillators it was possible to transmit supersonic sounds under water. This method of underwater sound transmission was further developed in Great Britain by Rutherford and his associates.

In Britain the echo-ranging equipment finally developed took its name from the initials of the committee and became known as ASDIC. The American name of "sonar," not adopted until 1943, is generated from the words: SOund, NAvigation and Ranging.

Naval Research Laboratory.

Sonar in the United States was developed in the face of great handicaps. The Government research work which had been started in the U.S. Naval Experiment Station at New London was transferred with reduced personnel to the Naval Engineering Experiment Station at Annapolis, Maryland, pending completion of the Naval Research Laboratory at Anacostia, D. C.

The work was costly and funds for scientific research in the military field were scarce. The expense had to be born by the Navy, and the Navy, in the era of the Washington Naval conference, was having financial difficulties. If it were possible and popular to sink battleships, it was even easier to wreck a research program. The underwater sound program was starved for funds. Scientists had to be imbued with both patience and patriotism to put up with the wages the Civil Service scale allowed for first-rank talent. But the Navy Department Bureau of Engineering, which in 1940 became part of the present Bureau of Ships, went energetically, if slowly, ahead.

In 1923 the work of the Naval Research Laboratory was transferred from Annapolis to the new station at Anacostia. This laboratory and the Submarine Signal Company were the only two organizations left in the field. The research program attempted both to improve the multi-spot listening device and to develop further the possibilities of echo-ranging.

The first types of echo-ranging gear to be tried out followed the principle demonstrated by Langevin, which was used in the experimental model XL equipment developed by the Naval Research Laboratory. Exhaustive tests at sea in 1928 showed that the equipment could give reliable results at ranges up to approximately 1200 yards. Such ranges obviously were inadequate for purposes of search, but the new equipment greatly strengthened the attack once listening contact was made with the target. Using the XL as a prototype a few model QA echo-ranging devices were installed on surface ships and experience with them confirmed the experimental test results.

Service experience also showed, however, that projectors of the quartz type, which require high voltages, were subject to breakdown due to the intrusion of moisture particularly in the insulation of the wires. A quartz projector is, moreover, sharply resonant and consequently can receive only a very small portion of the spectrum of supersonic noise.

To overcome these disadvantages of the quartz projectors experiments were conducted with another type of piezo-electric crystal, Rochelle salt. Equipments employing Rochelle salt projectors were built and designated as JK for supersonic listening and QB for echo-ranging. The results were gratifying in that the search range was increased.

Rochelle salt, however, displayed certain shortcomings. While the crystals were very efficient, they were electrically delicate and would burn out or melt if one tried to transmit with too much power. They also had to be protected from extreme temperature such as is occasionally encountered under the tropical sun.

Magnetostriction.

For this reason still another type of supersonic projector was sought and the answer found in the phenomenon of magnetostriction, according to which a ferro-magnetic material such as nickel changes its length when magnetized and conversely changes its magnetic state when strained. Projectors involving the magnetostriction principle were built into equipment of the QC class for echo-ranging and the NM class for depth sounding.

By 1933, the first QC gear had been built and installed on the new destroyers USS FARRAGUT and USS DEWEY. Simultaneously, the first standard QB installations were made on the new submarines CACHLOT and CUTTLEFISH of the SS-170 class. Thus, the beginning of standardized sonar gear coincided with the initiation of the expanded Navy building program.

Characteristics of Sea Water.

It is worth noting that all of the improvements to this earlier sonar gear succeeded in increasing by only a small amount the range at which submarines can be detected by echo means. This is because the limitations are generally not in the apparatus itself but in the sea water which carries the

sound waves. And the sea has its full quota of perversities to trouble the sound man.

It was in the hope of determining the nature of these limiting characteristics of sea water that, in 1936, the Submarine Signal Company aroused the interest of the Woods Hole Oceanographic Institution in the possibilities of an investigation. In January, 1937, a party of oceanographers and sonar engineers went to the Caribbean to investigate the problems of sound propagation in an attempt to correlate the anomalies with oceanographic data. This research, which disclosed the effect of thermal gradients on underwater sound transmission and which saw the first use of the bathythermograph for measuring these gradients, laid the foundation for the broad program of oceanographic research which Division 6 was to undertake during World War II and which is discussed in a later chapter.

CHAPTER III

DIVISION 6 ORGANIZATION

The Navy's Problem in 1940.

In June 1940, when NDRC came formally into existence, Secretary of the Navy Knox, in a request directed to Dr. F. B. Jewett, President of the National Academy of Sciences, asked that the Academy appoint a committee to advise him and his technical aide, Rear Admiral Harold C. Bowen, then Director of the Naval Research Laboratory, on ways and means to defeat the enemy's submarines.

This was a request that was welcomed by Dr. Jewett and by Dr. Vannevar Bush, Chairman of NDRC, both of whom believed that the anti-submarine problem was as urgent as the problem of meeting the air attack on Great Britain and one that presented even greater difficulties. The problem of undersea warfare -- as Dr. Bush was to express it later in a letter to Dr. Jewett--was "absolutely the kind of thing on which NDRC ought to take off its coat and get busy."

In response to Secretary Knox's request, the National Academy of Sciences named a committee of which Dr. Jewett and Dr. Max Mason of the California Institute of Technology were the most active members. In October 1940 a subcommittee was established, at Admiral Bowen's suggestion, "to study the scientific aspects of protection against submarine warfare" and to "ascertain the degree and adequacy of the present effort." For chairman of the subcommittee selection was made of Dr. E. H. Colpitts, former vice-president of the Bell Telephone Laboratories, who had been closely associated with Dr. Jewett in anti-submarine work during World War I. The other members of the subcommittee were W. D. Coolidge, H. G. Knox, Vern O. Knudsen, and Louis B. Slichter.

The members of the subcommittee spent a good two months visiting the Naval Research Laboratory, Navy shore establishments, anti-submarine craft, Woods Hole Oceanographic Institution, and the Submarine Signal Company. Some of their

findings were cheering; others were depressing. The subcommittee members found that the Navy had made good progress in the development of supersonic echo-ranging gear. But they also found that the Navy had been too pinched for funds to explore other means of submarine detection thoroughly. The existing detection gear was far ahead of the training of those who were to operate it. Basic information to enable its most effective employment was lacking and instruments for guiding an attack were badly needed.

Subcommittee Report.

As a result of their studies the members of the subcommittee, on 28 January 1941, made recommendations for a broad program of research and development. They stressed the importance of better methods of selecting and training sound operations, maintenance men, and officers. They urged that greater attention be paid to the fundamentals of undersea warfare, including the development of equipment for the measurement and recording of underwater sound, the determination of the sounds produced by various types of ships under varying operating conditions, the phenomena of sound propagation in the ocean, and the study of magnetic and micro-wave detection devices.

Following the submission of this report by the subcommittee, which by then had become popularly known as the Colpitts Committee from the name of its chairman, Dr. Bush and Dr. Jewett held a number of conferences with officers of the Navy. They were asked to submit to the Navy's General Board recommendations concerning the type of organization needed for a comprehensive study of the anti-submarine problem. In answer Dr. Bush and Dr. Jewett assured the Navy that both NDRC and the National Academy of Sciences were ready to do everything possible to get a broad program of research in the anti-submarine field under way.

Preliminary Activities.

In August 1940, following up a Navy suggestion, Mr. C.O'D. Iselin, Director of the Woods Hole Oceanographic Institution, had sent Dr. Jewett a memorandum concerning the Institution's facilities which might be useful in anti-submarine warfare research. After consultation with the Navy, a comprehensive outline was prepared on 19 September 1940 summarizing the principal objectives of an investigation of the oceanographic aspects

of the sound-ranging problem which Mr. Iselin had proposed. The program of work outlined for the Woods Hole Oceanographic Institution seemed so important that NDRC, on 27 September 1940, decided to contract with the Institution in the sum of $100,000 for a two-year study.

Meanwhile, looking forward to the time when, they hoped, there would be an organization to handle the anti-submarine research program, Drs. Jewett and Bush looked about for a man who could head it. They settled upon Dr. John T. Tate, Dean of the College of Science, Literature and the Arts of the University of Minnesota. Following his selection, Dr. Tate aided the Colpitts Subcommittee in its work, and was also given the responsibility of keeping in touch with the Woods Hole project.

Activities were under way in still another direction. In addition to participating in the conferences concerning an investigation of underwater acoustics, Dr. Slichter had been giving considerable thought to the possibility of detecting submarines by magnetic methods. With the assistance of the Submarine Signal Company, he had already done some work in this field; and he proposed to Dr. Jewett a scheme for magnetic detection of submarines which he thought might be of practical use.

A British scientific mission under the leadership of Sir Henry Tizard, which visited the United States in 1940, recommended that one or two American scientists be sent to England to confer directly with the Admiralty on the work which was being done in Great Britain on the detection of submarines. This recommendation was echoed in January 1941 by Dr. R. H. Fowler of the British Central Scientific Office. Following discussions with representatives of the Navy, Dr. Bush requested Drs. Tate and Slichter to make the trip. Dr. Slichter was to investigate, in particular, magnetic detecting of submarines. Drs. Tate and Slichter left on their trip on 7 April 1941.

Formal Navy Request.

Three days after their departure, on 10 April 1941, a letter came to Dr. Bush from Rear Admiral S. M. Robinson, Chief of the Navy's Bureau of Ships, stating that he had noted the recommendation of the Colpitts Subcommittee for an organization to investigate the problem of submarine detection.

"In as much as your organization was formed for the specific purpose of handling such problems," read Admiral Robinson's letter, "it is requested that you undertake this study."

This was the go-ahead signal for which NDRC had been waiting and planning. It was clear that the work should be undertaken in NDRC's Division C, of which Dr. Jewett was chairman. It was also clear that a vice-chairman should be appointed to correlate all the work in this specific field.

In consultation with Dr. Bush, Dr. Jewett prepared a memorandum outlining an organization which should have the following objectives:

"1. The most complete investigation possible of all the factors and phenomena involved in the accurate detection of submerged or partially submerged submarines and in anti-submarine devices.

"2. The development of equipment and methods for use of promising means for detection to the point where their final embodiment in form satisfactory for Naval operation can be undertaken by the regular Bureaus of the Navy."

The memorandum outlined the facilities which would be required for the work. A central control group would be needed to coordinate activities, arrange for work in special laboratories, and maintain liaison with the British and others engaged in anti-submarine warfare. Two special laboratories would be needed, and these would have to be located at or near Naval stations where suitable facilities would be available.

The plan called for a staff of the ablest scientists, engineers, designers and laboratory assistants, and contemplated access to university and industrial laboratories, and in particular to an oceanographic laboratory for fundamental research on the propagation of sound in sea water. The plan also called for the fullest cooperation by the Navy and the provision by the Navy of laboratory and marine facilities, and the necessary personnel for operating and policing them. The Navy, in short, would be expected to take full responsibility for the non-scientific aspects of the work.

It was recommended that at least one laboratory be provided on the Atlantic Coast and another on the Pacific coast. It was proposed that the Atlantic coast laboratory be located

at New London, Connecticut, and that its director be some one with long industrial experience. It was proposed that the Pacific coast laboratory be located at San Diego, California, its director to be some one with wide experience in fundamental research in the fields involved.

Program Approved.

The program thus outlined was approved by NDRC 18 April 1941 and on the same date was submitted to and approved by Admiral Robinson on behalf of the Navy. Dr. Bush immediately asked Dr. Jewett to get the program under way. Dr. Tate, who was still in England, was appointed Vice-Chairman of Division C and Chairman of Section C-4, which was the designation of the group that was to be concerned with anti-submarine warfare. Mr. T. E. Shea, vice president and chief engineer of Electrical Research Products, Inc., was asked to assume the directorship of the New London Laboratory. Dr. Knudsen, Dean of the Graduate Division, Southern Section, University of California, was asked to head the San Diego laboratory. Subsequently, Dr. Knudsen was succeeded by Dr. G. P. Harnwell of the University of Pennsylvania, and the New London Laboratory was directed, under Mr. Shea's general supervision, by Mr. T. Keith Glennan, formerly studio engineer for Samuel Goldwyn Studios.

On 29 April 1941 Dr. Jewett called a conference with Drs. Colpitts and Shea and G. B. Pegram, Dean of Columbia University's Graduate School, at which Dean Pegram was asked if Columbia University would enter into a contract to staff the East Coast Laboratory. Dr. Knudsen was requested to determine whether the University of California would agree to be the contracting agency for the San Diego laboratory. Dr. Colpitts and Dean Pegram were asked in the absence of Dr. Tate to take the preliminary steps to establish an organization.

The question of the Navy's part in providing facilities for the two laboratories was taken up at a conference held on 1 May at the National Academy of Sciences building in Washington, at which Admiral Robinson and Lt. Comdr. M. K. Kirkpatrick represented the Navy. Comdr. Kirkpatrick was named Liaison Officer to work with Mr. Shea in providing necessary facilities for the proposed New London laboratory.

On 19 May, Drs. Tate and Slichter returned from England, and on 5 June the following were officially appointed as members

of Section C-4: Carl D. Anderson, E. H. Colpitts, W. D. Coolidge, E. O. Lawrence, Max Mason, and G. B. Pegram.

As a first step in setting up a central headquarters, space was rented in New York City at 172 Fulton Street. Dr. Elmer Hutchisson was appointed Technical Aide and was given the task of setting up the New York office, with Miss Fern Sullivan as Administrative Assistant. Shortly thereafter, P. D. Foote, Philip M. Morse and T. E. Shea were formally appointed as members of Section C-4.

At the NDRC meeting of 12 June 1941, thanks to the extensive preliminary work which had been done, a comprehensive program of proposed investigations in the field of anti-submarine warfare was presented by representatives of Section C-4.

While the business of getting the organization under way was going on, there was great activity in preparing for the work to be done at the two central laboratories.

Central Laboratories Established.

The program contemplated for the New London Laboratory involved: Study of magnetic detection methods; study of the possibilities of optical detection methods; development and improvement of supersonic detection methods and equipment; study of types of sonic detection equipment; study, in cooperation with the Woods Hole Oceanographic Institution, of correlations between oceanographic conditions in the Atlantic with the performance of various types of detection equipment; study of background noises and methods of reducing them; and development of improved acoustical measuring equipment.

Within a few days following the approval of the anti-submarine investigation program, Mr. Shea, together with Commander Kirkpatrick and Mr. W. H. Martin, had investigated several possible laboratory sites in the New London area. After inspecting various locations, they finally selected the U. S. Coast Guard Base at Fort Trumbull as the most suitable site. Among other things, three piers were available. One of them would accommodate USS SEMMES, a destroyer which was used for experimental purposes. Some construction was necessary, but on 8 May 1941 Admiral Robinson wrote to Dr. Jewett saying that the necessary buildings would be erected.

Columbia University had agreed to operate the New London Laboratory on a contract basis and while construction of the buildings was under way, Mr. Shea began to assemble a staff. By 9 July 1941 construction was sufficiently near completion for the buildings to be partially occupied.

The laboratory was formally established on 1 July 1941 as the U.S. Navy Underwater Sound Laboratory with Lt. John B. Knight, Jr., USNR, as officer in charge. Administration of the laboratory was placed under the Commandant of the Third Naval District. As an experimental test vessel, the Navy made available a converted yacht, the USS SARDONYX.

It was necessary to make similar arrangements for accommodations for the San Diego Laboratory. The U. S. Navy Radio and Sound Laboratory was already in operation at Point Loma, but additional space was necessary. Dr. Knudsen together with Capt. W. J. Ruble, head of the laboratory, laid out space of approximately 6,000 square feet which seemed adequate at that time.

As originally contemplated, the San Diego Laboratory was to devote a major portion of its work to fundamental research. At a meeting of an advisory group on 7 June 1941, it was decided that immediate work should be begun on: the reflections of impulse sounds from boundaries in typical areas of the ocean near San Diego; investigation of the sound transmission properties of typical ocean areas; and work on the development of a predictor, or attack meter.

As the program developed, the San Diego Laboratory came to spend only approximately a third of its efforts on fundamental studies. The other two thirds were about equally divided between training and the development of training devices on the one hand and, on the other, the development of sonar devices for both anti-submarine and pro-submarine warfare.

Dr. Carl S. Van Dyke and Mr. L. P. Sivian were added to the San Diego staff as Assistant Directors, and the laboratory construction was completed by 26 June.

By the end of July 1941, the work of the Navy and NDRC staffs at San Diego had grown so fast that additional space was needed. This space was provided through the construction of two additional buildings which were completed within a few months. A converted yacht, the USS JASPER, and the E. W.

SCRIPPS of the Scripps Oceanographic Institution were made available to the laboratory as experimental ships.

Due to the urgency of its work Section C-4 did not confine itself to research at the two central laboratories, but reached out through numerous contracts to employ the research facilities and personnel of numerous university and industrial laboratories. In Cambridge, Massachusetts, the physicists of Harvard and of the Massachusetts Institute of Technology had been working under contract with the Navy and the National Defense Research Committee on problems closely allied to those of anti-submarine warfare.

On June 5, 1941 a contract was entered into with Harvard University for the establishment of the Harvard Underwater Sound Laboratory, of which Professor F. V. Hunt was designated technical director.

Numerous other contracts were entered into of which only a few can be listed here. Among the contractors were the: General Electric Company; Bell Telephone Laboratories; Gulf Research and Development Company; RCA Manufacturing Company, Inc.; Goodyear Aircraft Corporation; California Institute of Technology; Armour Research Foundation; Westinghouse Electric Corporation; Massachusetts Institute of Technology; American Can Company; Sangamo Electric Company; Newark College of Engineering; Electrical Engineering and Manufacturing Corporation; Leeds and Northrup Company; and the Iowa Institute of Hydraulic Research of the University of Iowa.

At the first formal meeting of Section C-4 on 11 June 1941, the program prepared by Mr. Shea and Dr. Knudsen for the two central laboratories were considered and approved. The programs were substantially those which had previously been outlined.

Staff Members.

The staff of the Fulton Street office of Section C-4 included Dr. Tate and Dr. Colpitts. In addition, there were several technical aides. Among the technical aides who served the Division and Section for longer or shorter periods were Elmer Hutchisson, L. G. Straub, L. F. Morehouse, R. H. Bolt, R. C. Hopgood, A. G. Anderson, Otto Wantuch, Dorothy Lasky, A. W. Barrus, David Keppel, and Laurence A. Moyer, who had barely been appointed when he lost his life in a test of underwater flares.

As previously mentioned, Miss Sullivan was administrative assistant for Section C-4 and later Division 6 until replaced late in the life of the Division by Mr. J. P. Lee.

Consultants to Section C-4 and Division 6 serving for various periods during the course of the work were: R. D. Fay, T. C. Fry, T. K. Glennan, D. G. C. Hare, W. V. Houston, F. V. Hunt, V. O. Knudsen, D. P. Mitchell, H. Nyquist, T. C. Poulter, R. S. Shankland, H. W. Sverdrup, M. S. Viteless, E. G. Wever, S. S. Wilks, and E. M. Wise.

A Section Committee was formed. The group met to consider critically the proposals for research work submitted and to recommend them, if satisfactory, for action by NDRC. Originally the Section Committee consisted of Dr. Tate as chairman, and Drs. Anderson, Colpitts, Coolidge, Lawrence, Mason, and Pegram. In August 1941 Messrs. Foote, Morse and Shea were added to the membership.

An important adjunct to the central administrative office was a group of scientists employed under a contract with Columbia University. This staff, known as the Program Analysis Group, carried on a continuous analysis of the work in progress. One of the group's first tasks was to make a statistical analysis of the probable effectiveness of an anti-submarine attack, taking into account, on the basis of probabilities, the characteristics of enemy submarines, of our own anti-submarine craft and their detection gear, of the ordnance then being used, and of sound propagation in sea water. The results of these early studies, showing that a depth charge attack had in all probability less than a five per cent chance of success, pointed out the necessity for work to be done on the development of anti-submarine ordnance.

As a consequence, the work of the Program Analysis Group was for a time split into two parts, with Dr. Slichter heading the continuing statistical work and Dr. W. V. Houston taking charge of other analytical studies.

Dr. Slichter transferred to other work on 31 December 1942 and Dr. Houston took over supervision of a group which was once more united and which by then had been entitled the Special Studies Group. The scope of the Group's work expanded and came to include development of torpedoes. Particular mention should be made of a section of Special Studies designated as the Sonar Analysis Group, which was set up to analyze and

correlate the results of the oceanographic studies conducted at Woods Hole and by the San Diego Laboratory. The Special Studies Group, in addition, followed up work on other projects, such as merchant vessel protection, sea water batteries, underwater sound detection ranging gear, and the preparation of Summary Technical Reports. (The last-named project later became the province of a special group known as the Summary Reports Group coming under the jurisdiction of the Office of the Chairman of NDRC.)

On 1 July 1941, a contract was arranged with the Western Electric Company authorizing the Bell Telephone Laboratories to engage in a study of testing and calibrating methods for use in underwater sound measurements and to develop standard instruments and testing equipment. Test stations were set up at Mountain Lakes, New Jersey, and Orlando, Florida. Later, on 15 April 1942, at a meeting called by Rear Admiral J. A. Furer, Coordinator of Research and Development for the Navy, it was decided that these laboratories should be operated by an independent organization having no direct interest in the development or manufacture of underwater sound devices. Accordingly, on the recommendation of NDRC, the laboratories were transferred to the Columbia University Division of War Research to be operated as the Underwater Sound Reference Laboratories under the direction of Dr. Robert S. Shankland, Professor of Physics at the Case School of Applied Science. The work of these laboratories is discussed in a later chapter.

Expansion of Activity.

Almost from the first, the work of NDRC's subsurface warfare group began to expand in scope. Starting with responsibility only for basic research and the development of devices to detect submerged submarines, it was not long before research and development work was being done in the fields of ordnance, especially aircraft ordnance, pro-submarine equipment, and torpedoes.

A similar expansion in types of activity took place. Late in 1941, a comprehensive program of assistance to the Navy in the selection and training of sonar personnel was started. This activity is described in Chapter XIII. A program of operational research, discussed in Chapter VI was begun in early 1942.

During the closing months of 1942, as various improvements in anti-submarine equipment became available or gave promise

of soon being available, it became apparent that Division 6 must give special assistance to the Navy in connection with the installation, maintenance and operation of anti-submarine devices. The answer was the establishment of the Field Engineering Group whose activities are discussed in Chapter XIV.

Another organizational development which took place comparatively late in the life of Division 6 was the establishment of the Pearl Harbor Division. The request for an NDRC evaluation and appraisal group at Pearl Harbor was originated by the Commander Submarine Force, Pacific Fleet in a dispatch of 12 July 1944. The Pearl Harbor Division was established in August and became a functioning organization as local representative of the NDRC New London Laboratory.

The Pearl Harbor Division furnished valuable assistance to representatives of other NDRC contractors. It was kept constantly up to date by the New London Laboratory. Thus they were able to bring the results of the latest research to bear in such fields of activity as: shipboard installation of equipments on which development was substantially complete; evaluation of equipment, methods and tactical procedures; sound measurements and investigations of improved sound measuring facilities; miscellaneous apparatus and methods investigations; selection and training, and engineering assistance to the selection and training group.

Originally designated Section C-4 of NDRC, the Underwater Sound Group at the time of NDRC's reorganization on 9 December 1942, became officially Division 6 with Dr. Tate as Division Chief. All research and development work of Division 6 was concentrated in one section, Section 6.1, of which Dr. Colpitts was Chief.

This chapter outlines some of the high-spots during the early months of organization of the research work on anti-submarine warfare and underwater sound. It does not pretend to be a complete history of the organization, but it is hoped that the following chapters will tell the story of the Division 6's growth and accomplishments.

CHAPTER IV

UNDERWATER ACOUSTICS

Submarine Concealment.

The problem with which the researchers of NDRC's Division 6 had to deal was technical and complex. They were asked to develop equipment which would detect a submerged submarine at a distance away great enough so that the combatant doing the detecting could do something about it--either run away, or attack before the submarine could get home with its torpedo. Also, the equipment must locate the submarine with sufficient accuracy to give an attack a reasonable chance of success.

Salt water is an excellent medium for concealment. Both theory and experiment show that it is almost opaque to all forms of electromagnetic waves--to radio, radar, infrared, ultraviolet waves and to ordinary light. Even in the clear waters of the mid-Atlantic, objects cannot be seen at any considerable distance. The magnetic field of a submarine can be used to detect its presence, but again this field is imperceptible beyond a few hundred feet. The same is true of the disturbance in the electrical properties of the sea caused by the presence of the metallic hull of a submarine in the vicinity.

Early in their study of the problem the scientists of Division 6 were convinced that the only form of radiant which could be employed to detect a submerged submarine at distances great enough to be militarily useful was sound.

A submerged submarine has certain weaknesses. Except under unusual conditions, it must keep under way in order to maintain its equilibrium, and a submarine moving under water, even at very low speeds, produces low-frequency noises from the machinery and from movements inside the hull. When the submarine is under way at high speed, as for example when it is trying to escape, high-frequency noises are produced by cavitation about the propellers.

The other weakness of the submarine lies in the fact that, though no leviathan, it is a bulky vessel. For example,

a 740-ton submarine has a length of approximately 244 feet. There are large areas of the submarine, like the conning tower, which are good reflectors of sound.

These two characteristics of the submarine--that it creates noise and reflects sound--complement a characteristic of sea water--that it is an excellent medium for the transmission of sound--far better than air.

Difficulties of Underwater Sound Detection.

But the business of transmitting and receiving sound under water is not a simple one. Particularly is this true of echo-ranging. Many other objects will reflect sound, including whales, schools of fish, patches of sea weed, the wake of another vessel, the frothy zone on the edge of a tidal current, and rocks and wrecks on the bottom.

When echo-ranging, it is not easy to get an echo in the first place or thereafter to keep contact with an elusive target like a hunted submarine. When a sudden sound is made under water, the ocean behaves very much like a large empty room with bad acoustic properties. The sound echoes and re-echoes, so that it is difficult to hear any small sounds such as a returning echo from a submarine. Especially in shallow water or in a rough sea, the reverberation may be so intense as to drown out the echo entirely. Underwater sounds from the motion of the ranging ship create a disturbance much like static on a radio.

Moreover, as will be seen, sound does not always travel in a straight line but is refracted due to changes in water temperature with depth which cause differences in water density and consequent changes in sound velocity. These temperature gradients bend the sound waves. Lastly, operators who have spent days in an empty ocean straining their ears for an echo, may become "ping happy" and be unable to detect an echo should one come in.

The improved German submarines of World War II could crash dive at approximately 2 feet per second and from periscope depth could reach 200 feet in approximately 90 seconds. They could dive to a depth of 600 feet or more making a 90-degree turn at 4 knots in slightly more than 2 minutes, so that 100 seconds after a submarine was seen at a given spot

on the surface, it might be more than 200 feet deep and anywhere within a circle of more than 1,000-feet radius.

Also, with the searchlight-type of sonar which was standard during most of World War II, the attacking vessel was forced to make the last part of its run blind. The sound beam of the attacking vessel travelled outward in a generally horizontal direction. Its vertical angle was wide enough to detect a submarine submerged at considerable depth, provided the range was great enough. But as the attacking vessel bore down on the submarine, the angle of the beam tended to pass over the submarine and contact was lost. Moreover, as the range was closed, the bearing changes required to keep the beam fixed on the submarine became so rapid that the sonar operator was unable to keep his gear properly trained.

Finally, there was the difficulty of personnel and training. Since no single piece of equipment so far developed is adequate both to locate and destroy a submarine, the coordination of equipment and crew is often more important to success than the detailed perfection of the individual elements. This is why the program of Division 6 laid so much stress on the selection and training of personnel.

Need for Basic Information

These were some of the factors which made the underwater sound program a difficult and challenging one and which, when Division 6 (then Section C-4) of NDRC was organized, highlighted the fact that lack of basic scientific information was a serious obstacle to the design of more effective underwater sound gear. For the intelligent development of such gear, basic information was needed concerning such behaviorisms of sound in water as the drop in intensity of underwater sound that has travelled between two points in the ocean; the influence on this intensity drop of refraction due to temperature gradients and other qualities; the amount, character and masking properties of extraneous background noise; and the reflecting properties of targets.

When NDRC first undertook basic research on the transmission of underwater sound it turned naturally to the Woods Hole Oceanographic Institution. Through continued contacts with the Navy in the years before World War II the members of the Woods Hole staff had acquired a realistic knowledge of

Navy problems. They had collected a substantial quantity of data, not only on underwater sound transmission, but also on relevant oceanographic problems. They had developed the bathythermograph, a device to make a record of water temperatures at all depths down to 300 or 400 feet. The bathythermograph had been perfected to the point where it could be used for temperature-depth measurements from vessels under way at 15 or 20 knots. They had developed applications of the refraction theory to underwater sound and while this theory was necessarily over-simplified, it proved extremely important in the interpretation of later information. In 1940, therefore, as already mentioned, NDRC entered into a contract with the Woods Hole Oceanographic Institution.

In the spring of 1941, in the light of further demands from the Navy, it became clear that the Woods Hole staff could not carry on alone. Not only was there need for more help, but it was felt that there should be a place where research work could be done at a location close to a large Navy establishment and near deep water, which the shallow Atlantic continental shelf made relatively inaccessible. San Diego seemed an excellent site since the 600-fathom San Diego Trough is located only 15 miles off-shore. NDRC, therefore, entered into a contract with the University of California for the establishment of an additional research group at the U. S. Navy Radio and Sound Laboratory (now the U. S. Navy Electronics Laboratory) at San Diego. The University of California's program as it developed drew a considerable measure of assistance from the Scripps Oceanographic Institution at La Jolla.

When experimental results began to accumulate from the work of the Woods Hole and University of California groups, it became desirable to assign a small staff of physicists and mathematicians to the analysis and evaluation of these research results. Employed under a contract with Columbia University, these scientists became known as the Sonar Analysis Group. Working in close cooperation with interested sections of the Navy, this group combined the basic research results obtained by different groups and determined the bearing of the research findings upon problems of design and operation.

The over-all program divided itself naturally into a number of fields of research, one of the principal studies being that of Underwater Sound Transmission.

Research on Underwater Sound Transmission.

The chief problem of transmission studies is the measure of the sound field of any source as a function of oceanographic conditions. When the sound is complex, such measurement requires a number of analyses of intensity and spectrum as functions of range and hydrophone depth. When the source can vary in depth, as does a submarine, that variation must also be measured. Time variations further complicate transmission studies, since a single pulse will sometimes travel by different paths to arrive at a hydrophone as a series of discrete or interfering pulses. Even when the source emits a steady tone of constant intensity, a hydrophone more than a few yards away receives a sound of fluctuating intensity.

In measuring the effect of oceanographic conditions on sound transmission, obviously, complete control of experiments is impossible and the separation of independent variables is exceedingly difficult. Experiments must be planned with great care because the subsurface "weather" cannot be planned. Large quantities of data must be collected in the hope that eventually all combinations of variables will occur.

In the Underwater Sound Transmission program, it was, of course, impossible to bring the sea to the laboratory, so the laboratory had to be put to sea. Studies were made in water of varying depth over bottoms of different character, in dead calms and near-gales, at various frequencies, at different times of day and night and in different seasons. Under such conditions it is not to be wondered at that it required months of experimentation to establish the effects of any one variable upon sound transmission.

Studies were not limited to the sound emitted by specially constructed transducers and standard echo-ranging projectors. Studies were made of the transmission of sound from ships and propellers, the output of various types of noisemakers and of explosions.

The general results obtained in the NDRC transmission studies may be explained on the basis of a few simple principles.

Sound travelling outward from a source always weakens with distance. Even though it travels through a perfect

medium, so that none of its energy is scattered or dissipated into heat, the wave front spreads regularly over a larger and larger area. Thus the total energy in the sound wave is spread even thinner and the concentration of energy in any region decreases regularly with the distance from the source.

If the source is assumed to be a point, the intensity of the sound which it radiates should decrease inversely as the square of the range. In actual practice, however, observed transmission losses can depart widely from the values predicted by the inverse square law. This discrepancy, which is sometimes called the transmission anomaly, is caused by the fact that (1) the ocean is a bounded medium and sound is reflected by its surface and bottom; (2) changes in the pressure, temperature and salinity of the ocean may result in changes in the velocity of sound and so change both the sound path and the way sound spreads; and (3) the ocean is something less than a perfect medium, so that energy is lost by absorption and scattering.

Research work so far has been unable to produce more than average figures for the value of the transmission anomaly under various conditions. Even when conditions are seemingly constant, observed transmission losses are highly variable.

Transmission is best when the water is isothermal; that is, when commonly-used measuring devices show no temperature variations with depth. When measurements are made with highly directional supersonic transducers in deep water, bottom reflection can also be ignored.

Under such conditions measurements show that a certain portion of the sound is absorbed in each thousand yards of sound travel. The amount of this absorption is measured in decibels per thousand yards, a quantity which is sometimes called the attenuation coefficient. In water which is isothermal from the surface to a depth of 200 feet or more the attenuation coefficient is relatively constant at any one frequency and is found to increase with increasing frequency. Thus it is about 3 decibels per thousand yards at 17 kilocycles, 4 decibels per thousand yards at 24 kilocycles and 15 decibels per thousand yards at 60 kilocycles. At very low frequencies, on the other hand, absorption is very weak and the attenuation coefficient seems to be almost negligible, so that sonic sounds trapped in a "sound channel" may travel for thousands of miles and still be heard.

It has been found that the attenuation of sound in sea water is 40 to 300 times greater than it should be on the basis of simple theory. This is one of the outstanding problems of underwater sound which still demands a scientific explanation.

Determination of an attenuation coefficient becomes much more difficult when temperature gradients are present in the top 100 feet of the ocean. When, for instance, there are gradients within 50 feet of the surface, the average attenuation in the shallow isothermal layer is generally about twice as great as it is when the isothermal layer is deeper, but it is also much more variable. Finally, when there is a strong negative temperature gradient beginning at the surface, transmission anomaly does not show a simple proportionate increase with range. Temperature gradients cause the sound rays to curve, so that the spreading of the sound obeys more complicated laws and obscures the effects of attenuation.

The researchers also undertook to study further the refraction theory which had been enunciated as the result of earlier work at Woods Hole, and which had also been developed independently before the war, both at San Diego and in Britain, to explain the observed variability of underwater sound transmission. Careful observations of what was called the "afternoon effect" had enabled Woods Hole scientists to establish the fact that it was produced by shallow negative temperature gradients.

The explanation was simple. Since the water near the surface was warmer than any below it, and since sound velocity increases with increasing temperature, any part of a wave front which was nearest the surface traveled faster than the part which was deeper and in colder water. Therefore, the whole wave front curved toward the region of lowest temperature, much as a twin-screw ship turns in the direction of its slower propeller. The sound beam was "bent" toward the bottom.

To put it in another way, all sound rays leaving the projector were bent downward. The one which left the projector at an angle, enough above the axis to become horizontal at the surface was the one which traveled farthest. It was the "limiting ray." Rays leaving at higher angles were reflected or lost at the surface. Rays leaving at smaller angles never reached the surface, since they were bent toward the bottom before reaching the top. Beyond the limiting ray was the "shadow zone," a region into which no sound could penetrate.

As the work progressed it was found that certain earlier assumptions, while useful, were not strictly true. Transmission studies begun at San Diego proved that shadow zones do not always occur when refraction theory predicts them, and that when they do occur they are not utterly soundless. Intensities within the predicted sound field, similarly, are affected by many things, though refraction may be extremely important.

Refraction theory is best borne out by the condition which led to its formulation. A predicted shadow zone materializes only when there is a strong negative gradient starting at the surface. Then the sound within the shadow zone is more than a thousand times weaker than that in the direct sound field. There is some sound in the shadow zone, it is true, but not enough to produce an audible echo from a submarine. What little sound there is probably results from the forward scattering of sound, perhaps by a deep "scattering layer."

There are no other conditions under which shadow zones materialize. With all other types of temperature distributions, no matter what the ray diagram predicts, sound intensity at any given depth diminishes regularly with range. There is no point beyond which the intensity drops sharply.

While basic research expenditures are of the nature of a capital investment, subject to amortization over a long period of time, many immediate returns were realized on the work done at Woods Hole and San Diego.

The problem of estimating maximum echo ranges is very much like weather forecasting. It is not perfect, but it is far better than guess work. Early methods of range prediction were fairly simple. In fact, they turned out to be too simple. But, the prediction method that finally evolved contains two different procedures, one for deep water and one for shallow water. Under certain conditions the method used in deep water may be used in shallow water as well. When these conditions are not found, however, the problem of range prediction in shallow water is so complicated by bottom reflections and reverberations that it must be solved by entirely different means. The range tables now in use are based not only upon transmission measurements, but also upon studies of noise, reverberation and recognition. Even so, it must be admitted that they give only approximate values and it is to be hoped that the studies may be continued and that they will result in new methods which will prove more accurate and less difficult to use. It is particularly desirable that research be continued into a system of prediction for use in shallow water.

Many combat vessels transmitted to the researchers data which were incorporated into the general pattern of the findings. On the basis of all the facts thus at hand, the research workers were able to prepare sound ranging charts which gave a general indication of the conditions which might be expected to be found in various areas. Published by the Hydrographic Office, these charts were disseminated widely throughout the Fleets and were used in the planning of antisubmarine operations and in the routing of convoys. With the development of better methods of predicting maximum echo ranges, not only could the commanding officer of a convoy plan the best disposition of his escort vessels, but the sonar operator could use the information to determine the best settings of the dials on his gear and plan his search operations more effectively. A bathythermograph on at least one escort vessel of every convoy or other unit became standard equipment, and a standard form of "sonar message" was devised to transmit sound range predictions to other escort vessels.

While the transmission program was one of the most important phases of the basic research carried out by NDRC, it was by no means the only one. Measurements of the noise output from ships and submarines, calibration measurements on all types of sonar gear, the acoustic properties of wakes - these were among the many subjects studied for various special purposes.

Ships, Submarines and Marine Life as Sound Sources.

Studies were made of the characteristics of ships and submarines as sound sources. Hundreds of measurements were made of the sound output of all types of vessels, ranging from submarines to battle ships and aircraft carriers. These were important in the design of acoustically actuated underwater mines and also in the computation of maximum listening ranges obtainable with Navy sonar gear.

One collateral observation showed that some carriers had "singing" propellers. It was found that by a relatively minor change in propeller design this very undesirable type of sound could be eliminated. A number of general conclusions of permanent value were reached, although it should be noted that essentially these data are ephemeral. The sound output of a ship is directly dependent upon maintenance and may be affected by the installation of new auxiliaries. Slight injuries to a propeller such as can be caused by a bit of driftwood may

raise its sound output many decibels. The findings, therefore, pointed to the necessity of maintaining a continuing program of measurement coordinated with a program of corrective measures.

An entirely different set of sound sources, those occurring in nature, were also studied by Division 6. For these background noises, which interfere with the detection of wanted sounds, there are many causes, ranging from breaking waves to marine life, such as porpoises, snapping shrimp and croakers. The data on biological noise were used by the Bureau of Ordnance in the design of acoustic mines.

Standards and Calibration Studies

Standard methods for the measurement of underwater sound are important in two general ways. First, they assist in the development and production of sonar equipment; and second, they are essential for the checking and monitoring of the performance of the acoustical gear at sea.

The devices and gear used by the Navy in combat were the result of a coordinated effort by many groups leading through many stages from research finally to operation at sea. At many points in this sequence, especially during the research stage and the development of pre-production models, experience proved that progress was greatly accelerated when quantitative measuring techniques were available to obtain reliable physical data expressed in the terms and units standard for the art. It was also important that gear installed on shipboard be periodically checked by standard measuring techniques to be sure that it was functioning properly. The instruments used in these monitoring measurements had to be calibrated in terms of the standards used for the whole field of underwater sound.

With this basic situation in mind, NDRC when it undertook in 1941 to co-operate with the Navy in underwater sound research and development gave prompt consideration to the further development of instrumentalities and techniques for precision measurements in underwater sound. The program of investigation and development was conducted by the Underwater Sound Reference Laboratories, established by the Columbia University Division of War Research under a contract with OSRD. USRL's director was Dr. R. F. Shankland. In planning the NDRC program, full use was made of the practices currently employed

in industry, and especially the experience gained by U. S. and British Navy laboratories during the years between the two World Wars.

At the outset it was, of course, impossible to forecast all the types of acoustical devices that developments in the military situation would require. The program, therefore, was as broad in its scope as possible.

The work on standardization sought not only the development of instruments and techniques required for precision measurements, but in addition careful consideration was given to the establishment of standard terms, basic units and reference points, so that the results of all quantitative measurements could be accurately and conveniently expressed.

The work was carried forward actively throughout the war and at the close of hostilities progress had brought developments in this field to the stage where measurements could be made with a precision at least as great as heretofore possible in air acoustics.

At the war's outset, no single type of underwater acoustical device was sufficiently reliable to serve either as a standard hydrophone or a standard source of sound. At the close of the war, acoustic systems of the greatest versatility and efficiency were in use and under development. At each stage in the evolution of these devices, corresponding improvements were called for in the standardizing techniques and instrumentalities needed for precision measurements.

Equally important to the specification of test equipment for the work was the formulation of measurement techniques and calculation routines. First in importance was the choice of frequency range in which calibrations were to be made. In the beginning, this range was from 100 cycles per second to 50 kilocycles per second; by the close of the war it extended from 2 cycles per second to 2.2 megacycles per second.

Provision was made for the study of the effect of other pertinent physical factors on performance such as the temperature and pressure conditions encountered by gear in the ocean. This included the ability to produce temperature variations similar to those encountered in both the arctic and tropical regions, as well as to reproduce the hydrostatic pressures to which a submerged submarine is subjected during actual operations.

By keeping in constant touch with the Services and the NDRC and industrial laboratories developing new equipment, the Underwater Sound Reference Laboratories were able to anticipate well in advance the kinds of precision measurements they would be called upon to make.

The expansion of testing facilities which this policy required ultimately made available four complete calibrating systems for the frequency range from 20 cycles per second to 150 kilocycles per second; two of these systems being installed at Mountain Lakes, New Jersey, and two at Orlando, Florida.

Research and development work on standardization was carried on along both theoretical and experimental lines. The theoretical program included the definition and adoption of standard terms and units for expressing the results of underwater sound measurements, and rating the efficiency and performance of acoustical devices. Theoretical and experimental work was carried on for the specification of optimum testing depths, and distances; and a schedule of computation procedures for accurate and rapid preparation of the test data in report form. The choice of terms and units was adopted with the aid of a Hydrophone Advisory Committee appointed by the Coordinator of Research and Development of the Navy. The definitions and terms finally adopted have been recommended by the Navy for adoption by the American Standards Association for underwater sound.

The classes of acoustical gear upon which calibrations and tests were made by the USRL in the course of the war included: echo ranging sonar; shipboard and submarine listening systems; acoustic elements for the radio sonobuoy; harbor defense installations; and quality control instruments.

Among the wide variety of new acoustical techniques perfected during the war may be cited the use of enclosed testing tanks where side wall reflections were eliminated by the use of short pulsing techniques utilizing developments in radar circuits. Without these methods a large number of calibration and factory production test procedures would have been wholly impractical.

During the period of operation of the Underwater Sound Reference Laboratories by Division 6, the resulting improvements in quantitative measuring and standardizing techniques were made available to all authorized organizations. This

information made it possible to install production testing methods for use in the factory that permitted great improvement in the control of the quality of acoustical gear not heretofore realized. By working closely with groups concerned with field tests and measurements and making available to them improved techniques, it was possible to improve the effectiveness of practically all acoustical measurements made at sea.

Notable among these projects was the program for the measurement of the noise output from American submarines when operating in combat areas. The acoustical measuring sets developed at the New London Laboratory for this work were all calibrated at regular intervals by the Underwater Sound Reference Laboratories.

Service gear when installed and ready for use had to be subjected to accurate tests and checks if it was to function efficiently. The acoustic monitor developed at Harvard University, and described later in this volume, made possible the checking of the acoustic operation of every destroyer's sonar while at sea. The readings of these monitors were all ultimately referred to the acoustic standards used for calibration purposes.

As a result of the measurement and standardization program, much important information and many new instruments and techniques were made available to the engineer and scientist for precision measurements that will find application in many fields of peacetime work. The standard instruments themselves incorporating the wartime advances in the use of new piezoelectric crystals, such as ammonium dihydrogen phosphate, will find application in many lines of acoustical work. In addition, better methods for the utilization of quartz and Rochelle salt crystals were found as a by-product in the development of better standard instruments.

In a similar way, the improvements in the efficiency of magnetostriction devices and electromagnetic instruments will contribute to many lines of peacetime acoustical engineering and related fields. These latter improvements were the result of the full utilization of new magnetic materials and fundamental improvements in the theory and practice of magnetic circuit design. The power handling capacity of acoustic gear, the necessity for much wider frequency response, and for high fidelity equipment when used with very short pulses and

other special signals have resulted in refinements in the art of instrument design and associated electrical circuits that promise to find many useful applications.

Acoustics of Wakes.

When the development of measures to counter the enemy's acoustic torpedoes became urgent, it was obvious that the acoustic properties of wakes would determine the success or failure of these devices. The sound output of the ship's screws was also an essential datum. Consequently, basic research on the properties of wakes became a high priority task assigned to UCDWR and to other groups working under Division 6.

Pro-submarine Research.

As with other parts of the Division 6 program, as the war progressed, the basic research program was able to turn from anti-submarine operations to pro-submarine operations. A scientific study was undertaken of the effect of subsurface weather on the diving operations of our own submarines.

Special submarine supplements to the sailing directions published by the Hydrographic Office included not only information on diving and sound conditions, but also on wind and water currents, bottom topography and character and so on. All three NDRC groups that were participating in the program cooperated in the preparation of the supplements and a special group of writers and cartographers was established at San Diego headed by a geologist on leave from the Geological Survey of the Department of the Interior. Numerous other special charts were prepared by NDRC personnel, among them a series of bottom sediment charts and special charts requested in connection with amphibious operations.

Oceanographic factors also played an important part in the design, location and operation of harbor defense equipment, especially in the location of listening hydrophones and echo-ranging gear mounted on the ocean bottom. On both the Atlantic and Pacific coasts, NDRC laboratories collaborated with the Navy in special acoustic surveys designed to obtain useful information applicable to harbor approach areas.

The use of fundamental oceanographic data to improve the basic design of sonar gear, while less widespread than the

operational uses, was yet of great importance. The quantity of information obtainable on underwater sound transmission, background noise, reverberation and other factors, made it possible, by the end of the war, to predict at least approximately the performance of a particular piece of equipment before it had even been built. The Sonar Analysis Group in New York, for example, computed the expected performance of standard types of listening gear and also considered the special advantages to be gained from using listening gear operating at low available frequencies.

CHAPTER V

TRANSDUCERS

Research on Magnetostriction Transducers.

As is inevitable in the hurry of war, much of the scientific work devoted to the production of new tools for subsurface warfare involved the type of research that is commonly called developmental, rather than the type which may be called fundamental or basic. Yet considerable research of the latter sort was done in the field of transducer development. Transducers were required in a wide variety. Sonar devices were made for listening, where their function was to make possible the perception of noise-making objects such as a ship's propeller or the enemy's sonar gear. They were made for echo-ranging to detect the presence of submarines and other objects; for sounding to measure the depth of the water; for masking, to interfere with the performance of enemy sonar; and for decoying, to make sounds and noises to confuse and mislead the enemy.

Although the word "transducer" by its Latin derivation may properly be used to describe any device which converts energy of one type to energy of some other type, in this volume "transducer" is used to describe the device which converts electrical energy into acoustical energy and vice versa. This conversion can be accomplished in several ways: electrodynamically, as in the convention radio loudspeaker; by the magnetostriction effect; and by the piezoelectric effect.

A substantial program of basic physical research in magnetostriction was conducted by three of the Division 6 contractors in parallel with a program for the development of transducers for experimental and service use. These contractors included the Bell Telephone Laboratories, the Harvard Underwater Sound Laboratory and the Columbia University Division of War Research Laboratory at New London. As a result of this research effort, the fundamental scientific base for further development work in magnetostriction has been broadened and strengthened rather than restricted by the work concentrated on applications useful in subsurface warfare.

The principle of magnetostriction is comparatively old, but its technological utilization dates from the middle 1920's. In the period which elapsed following the pioneer work of G. W. Pierce, the development of magnetostriction transducers as underwater sound projectors was carried forward, as previously described, by the staff of the Naval Research Laboratory. Magnetostriction transducers are well adapted for use in the frequency range extending from 10 to 100 kilocycles, or perhaps even higher, and can easily produce sustained sound waves of intensities sufficient to produce cavitation in all ordinary liquids.

The echo-ranging sound projectors available and in use at the beginning of World War II left much to be desired. They were the product of experimental trial and error, and of intuition, rather than the result of accurate quantitative analysis.

The Harvard Underwater Sound Laboratory carried on throughout the war a research program devoted to elucidating the fundamental factors affecting the performance of magnetostriction transducers. As a result of the studies of this group and the collateral investigations of the other laboratories engaged in similar work, it not only became possible to construct improved transducers for sonar and ordnance purposes, but also to put the problem of designing such transducers on a sound engineering basis which actually permitted calculation of performance in advance of construction.

The research program carried out by HUSL and by BTL and New London can be described under three broad headings:

First of all, it was necessary to make a careful, theoretical analysis of the electromagnetic conversion process. Emphasis was placed upon a mathematical analysis of the magnetostrictive coupling between the electrical driving circuit and the active material of the transducer, so that this fundamental characteristic of the transducer could be described quantitatively in terms of the magnetic properties of the active material and the configuration of the electric and magnetic circuits. This study made it possible to draw equivalent electrical circuits which could represent the performance of the electro-acoustical system, not only in a qualitative way, but also with quantitative precision.

It was also necessary to make extensive measurements of the magnetic properties of the magnetostrictive materials

available for use in transducer construction. Various alloys proved to have properties especially useful in transducers operating without benefit of an external source of magnetic polarization.

Bell Telephone Laboratory studies indicated that no single material is universally "best" for the construction of magnetostriction transducers. The requirements for such an ideal material are inherently contradictory. High reversible permeability and high coercive force are both desirable, but they usually increase and decrease in opposite directions, as the composition and treatment of the material are varied. Fortunately, it was found that useful compromise values could be obtained.

The third major phase of fundamental research in magnetostriction transducer design concerned the analysis of the complex vibrating system by which magnetostrictive strains are converted into the vibration of a radiating surface in contact with the water medium. Both the New London Laboratory and HUSL conducted active programs of transducer design in which various configurations of the magnetostrictive material were employed in the attempt to secure desirable performance in the final transducer.

Eddy currents constitute one of the most serious sources of internal dissipation in magnetostriction transducers. In units employing radial or longitudinal vibration of nickel tubes, this effect is especially prominent, and led to many schemes, some practical and some impractical, for reducing the eddy currents by lamination. Considerable success was realized in minimizing the eddy currents by using stacks of flat laminations.

The principal types of magnetostriction transducers made available by this research program may be classified as follows:

(1) Radially vibrating tubes

(2) Asymmetrical Laminated stacks

(3) Laminated ring stacks

(4) Tube and plate transducers

(5) Miscellaneous forms.

A. L. Thuras, O. H. Schnuck, F. P. Bundy, M. H. Hebb, and L. N. Miller made important contributions to magnetostriction transducer development.

Almost every laboratory engaged in applications of subsurface sound, devoted some attention to the analysis of the directional patterns of sound radiators, the primary objective being to eliminate the spurious sound radiation characterized by minor lobes. As a result of the work of H. Brooks and others it was possible to establish specifications for producing directivity patterns of any degree of sharpness and freedom from minor lobes, provided the surface of the radiator could be excited according to any prescribed pattern of phase and amplitude. These mathematical conditions had a physical counterpart in the construction of transducers as arrays of small stacks of thin laminations whose individual excitations could be controlled in accordance with the theoretical requirements. One typical transducer constructed on this basis was designated SPEP and exhibited an excellent directivity pattern as well as the high efficiency characteristic of the laminated stack construction.

Theoretical consideration was also given to the formation of sharply directive sound beams by multi-element cylindrical arrays of transducer elements. Proper specifications for the distribution of amplitude and phase among the elements of the array were found and conditions were established for the rotation of the directive patterns so formed about the axis of the array without distortion, by suitably modulating the amplitude and phase of the excitation of the individual elements.

As is true with most research programs that of Division 6 on magnetostriction transducers uncovered many new problems for each one solved. Most of the transducer designs which were studied related to vibrating systems of a single degree of freedom. Further study could profitably be devoted to wide range transducers possessing additional degrees of freedom. In the field of magnetostrictive materials there is still room for improvement of the factors which increase the tightness of the coupling between the electrical and mechanical circuits and for further reduction of the eddy current losses.

Research on Piezo-Electric Transducers.

Piezo-electric materials are crystals which when compressed in particular directions accumulate electrical charges

on certain of their surfaces. Conversely, when an electrical field is established across these surfaces the crystal expands or contracts in certain directions. The most common of these materials are quartz, Rochelle salt, and ammonium dihydrogen phosphate ($NH_4H_2PO_4$). The first occurs naturally in certain parts of the world, while the latter two may be grown synthetically.

The French physicist Langevin made the first sonar transducer by cementing a mosaic of quartz crystals between two heavy steel plates, which also acted as electrodes. Langevin's "sandwich" became the prototype for the very successful ASDIC transducer developed by the British Admiralty, and a similar unit was developed for the U. S. Navy by the Naval Research Laboratory.

Since most quartz is imported into the United States, an early effort was made to design American transducers around more available material. The success of the Brush Development Company in growing large flawless crystals of Rochelle salt early suggested the use of this material in place of the rarer quartz. Rochelle salt, however, has certain disadvantages. It contains water of crystallization, which makes it difficult to handle and also seems to limit the amount of power which may be applied to it. At about 55 degrees Centigrade, it decomposes.

The Brush Development Company introduced a new piezo-electric crystal which came to be called ADP (ammonium dihydrogen phosphate), which has certain important advantages. It has no water of crystallization and decomposes at 190 degrees Centigrade, being useful up to about 130 degrees Centigrade. This material soon became available in sufficient quantity to replace Rochelle salt, so that now, with few exceptions, all new transducers are being designed around the better properties of ADP.

While the Harvard Underwater Sound Laboratory and the New London Laboratory were working on magnetostriction units, the University of California Division of War Research at San Diego worked on the development of piezo-electric transducers. The Brush Development Company and the Bell Telephone Laboratories, working principally under direct Navy contract, also did notable work and freely exchanged information with the laboratories working under NDRC.

The UCDWR Transducer Laboratory, under the direction of F. N. D. Kurie, obtained the services of George Argabrite, an

engineer with practical experience with air microphones, and T. F. Burke, a physicist. These two men formed the nucleus around which the UCDWR Transducer Group was built. Somewhat later they were joined by Keith Burton, technician. Eventually it was possible to make a reassignment of duties at UCDWR so that Dr. Glen Camp could devote his full time to piezo-electric research. Dr. Camp was particularly well qualified by virtue of his mathematical training. By the middle of 1941 it was possible to set up a Research and Development Group headed by Dr. Camp as a branch of the Transducer Laboratory. This group ultimately included Dr. Fred Uber, Dr. Bourne Eaton, Dr. David Kalbfell, and Mr. Burke. All of these men were experimental physicists with good theoretical backgrounds. They were originally assigned the job of surveying the field and were always, as far as the urgency of the war permitted, allowed free rein in selecting the problems on which they worked.

The problem of irregularities in the performance of transducers was attached by the UCDWR group in two ways. Dr. Camp made a thorough study of the complex vibrations of a crystal and was able to develop mathematical methods of dealing with them. These studies enhanced the understanding of the problem to a point where fairly accurate predictions of vibrational characteristics could be made. A further study was made experimentally by Dr. Eaton, who became interested in the question of why the directional patterns of transducers often failed to agree with theory. He built a small probe microphone with which he could explore the variation of velocity over the vibrating face of a crystal array. This showed that such an array does not move back and forth like a piston, but has great irregularities. These are particularly bad when the crystals are cemented to a backing plate. Moreover, a single crystal is shown to vibrate in very complicated ways, depending on its dimensions and the amplitude of the driving force.

Applying this method to a backing plate or bar has led to a better understanding of the tortional and flexural vibrations of these driven components. It has been assumed that the backing plate stretched and contracted only in the vibrating direction. Actually, it was found that it bends and twists and writhes as though possessed. These parasitic motions sap energy from the desired motion, and thus impair the efficiency of a transducer and spoil its beam pattern. Slotting the backing plate, breaking it up into a number of

isolated sections, or altering the location of the crystals on the plate often will serve to change the frequency of parasitic oscillations, so that they cease to be troublesome.

It was found that the simple theory developed for slender crystals did not take account of frictional load on faces other than the radiating end. Thus, an array of crystals is imagined as moving back and forth like a piston, but in an actual transducer, since crystals are soluble in water, the motor is usually in a box filled with some liquid, most often castor oil, which serves to transmit the sound to the sound window (usually rubber) and also to insulate the electrodes from each other. The motion of the crystals is such that the radiating end must push the viscous castor oil aside while the sides slip through it. Both of these motions absorb energy, and since they contribute nothing to the radiated sound, tend to reduce the efficiency of the transducer. When the spaces between the crystals are too small, the energy absorbed in moving the oil in and out of such narrow crevices can be very large. Many of these matters are not obvious at first glance because of the minuteness of the motions under discussion. Actually the motion of a crystal in a transducer is not much greater than a wave-length of light, and failure to recognize many obscurities in transducer performance is traceable to this.

W. P. Mason of the Bell Telephone Laboratories developed an equivalent circuit for a piezo-electric transducer which aids and simplifies the task of dealing with a practical design. The idea of an equivalent circuit is old but useful in applied acoustics. The Mason circuit is one to which all more complicated circuits must reduce when applied to this particular case. It is, therefore, a check to be applied to other circuits.

Dr. Camp sought to extend this to practical transducers and evolved a circuit which successfully took into account the finite size of actual crystals, loadings on all crystal faces, tangential as well as normal, and the coupling between various modes of vibration insofar as they are practically important. As it must, Camp's circuit included Mason's as a limiting case.

Even though an equivalent circuit is of very considerable aid in simplifying design calculations, it still involves long and tedious work. A small group of computers under Mrs. Alice Keith was set up at UCDWR to make such calculations.

It proved possible in many cases to devise equivalent circuits whose components were real. It was then possible to

construct the circuit from resistances, condensers and inductances which might be found in the stockroom. By making electrical measurements, on such a circuit, one could quickly make design adjustments simply by turning knobs. Thus the researchers had a computing machine of great flexibility and convenience. This device, which was called the "LCR simulator," proved extremely useful as a design aid.

Much work was done on cemented joints, on types of cement, and on the baking and conditioning procedure. Dr. Fred Uber noticed that ADP crystals would tolerate the temperatures required for the Chrysler cycle-weld process. He was thus able to bond the crystals to rubber so that either the rubber or the crystals ruptured before the bond failed. This technique permitted the attachment of crystals directly to the rubber sound window and eliminated the need for the castor oil. Such transducers obeyed theoretical predictions much better than those using the castor oil. Methods were found for strengthening the rubber windows so that such cycle-welded units promised to be as strong as those made otherwise.

In addition to NDRC, other agencies, especially those responsible for the continued availability of crystals, contributed indispensably to the furtherance of transducer engineering. The Brush Development Company before the war had designed and built a number of plants for growing Rochelle salt crystals and had set aside a large stock pile of crystal bars. Thanks in large part to the attitude of Mr. A. L. Williams and Mr. W. R. Burwell of that company, the country had a reserve of crystals needed for the heavily increased demands occasioned by war. It was their continued support of fundamental research in crystal physics and physical chemistry which led to the introduction of ADP by Dr. H. Jaffe and his associates. By the end of the war, the plants of the Brush Development Company and the Bell Telephone Laboratories were turning out a supply of ADP crystals sufficient to meet military requirements. A pilot plant for the further study and control of ADP was constructed and put into operation by the Naval Research Laboratory.

Under a direct contract with the Navy, the Bell Telephone Laboratories also engaged in the development of many excellent transducers and supplemented this work with studies of fundamental nature. Under W. H. Martin, a group consisting of A. C. Kellar, W. T. Mason, and their associates, did most valuable work on crystals, cements, electrodes, oils, rubbers and nearly every other phase of transducer engineering.

The sound division of the Naval Research Laboratory under Dr. H. C. Hayes was active in the basic study of crystal vibrations. NRL has differed from UCDWR in the philosophy governing this latter work. NRL has preferred the direct solution of the differential equations with suitable boundary conditions rather than the representation of the problem by an equivalent circuit. It is highly desirable that both methods be followed, the one to act as a check on the other. The direct method is somewhat more cumbersome to use, but when aided by a comprehensive report recently published by W. J. Fry, J. M. Taylor and B. W. Henvis of NRL ("The Design of Crystal Vibrating Systems") can probably compete for accuracy and speed with calculations based on the equivalent circuit. The method of direct solution, however, lacks the convenience of the LCR simulator.

CHAPTER VI

ANTISUBMARINE OPERATIONS RESEARCH GROUP

Purpose of Operational Analysis.

An innovation of World War II was the addition to the Navy staff responsible for anti-submarine operations of a specialized civilian scientific and technical group for research, analysis, and evaluation.

The British had first felt the need for a closer tie-up between those in charge of operations and scientific experts. In so complex a war as that against the U-boat it was essential that there be a clear channel by which operational data might flow to an analytical staff, and an equally clear route by which the results of scientific analysis of the data might be passed back up to the operational level. The secret nature of much of the data made it necessary that the scientific group be an integral part of the highest operating staff.

Thus, by a natural development, completely analogous to the earlier development in England, scientific aid in anti-submarine warfare began by assisting in the design and production of equipment and finally extended to assisting in the planning of operations.

The need for operational analysis research had been foreseen as far back as the time of the Colpitts Committee. As the members of the committee explored and weighed the Navy's readiness to enter the war against the U-boat, it was clear that it was not merely a question of gear. It was, as well, a question of how well the gear operated under actual or simulated service conditions. It was also a question of tactics and tactical doctrine, of personnel and training, and of operations records.

It was a matter of finding the right answers to questions like the following:

If a convoy were attacked by a submarine, and the submarine succeeded in breaking through the escort screen and

sinking some of the convoy vessels, what was the cause and was there a cure? Was it the method used in routing convoys, or was it the spacing of the ships in the convoy? Was it because escort vessels were too few in number, or were they improperly disposed? If the convoy commander could show that he had followed doctrine, was the doctrine at fault? Did the detecting gear perform as expected? Was any fault to be found in the performance of personnel? And - a major item - were the operations records in current use sufficiently complete so that they contained all the data necessary to make an analysis which would improve future operations?

The Navy itself lacked the means to make detailed quantitative analyses of operational experience. Virtually every person in the Navy with any operational experience in anti-submarine warfare had been hurriedly assigned to go out and sink submarines or carry out important executive tasks. Moreover, these technical analyses called for specialized mathematical and scientific skill which few Naval officers might be expected to possess.

Navy Request.

On March 16, 1942, Captain (now Rear Admiral) Wilder D. Baker of the Anti-Submarine Warfare Unit of the Atlantic Fleet asked NDRC to establish an Operational Research Group.

On 20 March, Dr. Tate, as Chief of Division 6, asked Dr. P. M. Morse, Professor of Physics at the Massachusetts Institute of Technology, to head the group. Then a search started for the best possible men to form the initial staff. The laboratories of NDRC and laboratories and institutions not yet engaged in war work combed for personnel contributions. A loan of the services of Dr. William Shockley of the Bell Telephone Laboratories was obtained so that he might become the group's Director of Research and Assistant Supervisor. Dr. M. E. Bell and Mr. J. R. Pellam were contributed by the Harvard Underwater Sound Laboratory. The first statistical studies of depth charge attacks had been carried out for Section C-4 by Professor Wilks. He now agreed to contribute part of his time in order to get the new group started. As Group M, the Operational Research workers started to function under the existing contract (OEMsr-20) with Columbia University. During this first period, Captain Baker acted as the service liaison officer.

As the possibilities of operational research began to grow, so did the membership of the group. By 1 May 1942 the staff consisted of seven scientists, and by 1 January 1943 there were a total of thirty. By the end of August 1944, the group had grown to fifty, of whom seven were mathematicians, sixteen actuaries, eighteen physicists, five chemists, three biologists and one architect. Of the total, twenty-eight were Ph.D's or were full Fellows of the Actuarial Societies. Though retaining the title of Research Group M for administrative and financial contacts, the group had a more formal title, the Anti-submarine Operations Research Group (ASWORG) for use with the Navy and for classified reports.

ASWORG's Headquarters.

The first home of ASWORG was in the quarters of the Anti-submarine Warfare Unit of the Atlantic Fleet, at the headquarters of the First Naval District, 150 Causeway Street, Boston, Massachusetts.

Beginning in June 1942, the main headquarters of the group was gradually transferred from Boston to Washington, where offices had been obtained in Temporary Building 2, Office of the Navy Department. Later, after one or two moves, permanent quarters for the group were found in the main Navy Building on Constitution Avenue in Rooms 4303 to 4313. The installation of the members of the group assigned to Eastern Sea Frontier was accomplished by the first of July.

One advantage of this closer relationship with the Eastern Sea Frontier was that contact could be maintained with the Army Air Forces First Bomber Command which provided many of the long-range bombers used in anti-submarine patrols along the Eastern coast. In order that members of the group might observe experiments, both tactical and equipmental, which were being carried out under Colonel W. C. Dolan, a number of the Army air fields were visited, in particular Langley Field.

Field Assignments.

It was early realized that it was important for the staff of Group M to keep in close touch with actual operations. It was in the summer of 1942 that in keeping with this policy a number of members of the group, including Dr. Shockley, Dr. A. F. Kip, Dr. R. F. Rinehart, Dr. M. E. Bell, Mr. Pellam,

Dr. F. L. Brooks, Dr. J. J. Steinhardt, were assigned to various naval bases in the Caribbean, North and South Atlantic.

It is not too much to say that probably the most important work of Group M during the first year of its life was the work done at the outlying bases; for the work at the Washington headquarters was necessarily work of a long-range type which was inevitably slower in reaching its full effectiveness.

As organizational practice developed, it became the rule to exchange men between the central headquarters at Washington and the outlying bases. This practice had a dual advantage. To the men who had been held down to detailed work in a Washington office, it offered the stimulus of getting nearer to the war. It brought back to Washington men with first-hand knowledge of field problems and the personnel who had to deal with them.

Headquarters Staff.

All this is not to minimize the importance of the work being done by the members of the group stationed at the central headquarters in Washington. It was at the Navy Department in Washington that the official orders were issued and the general doctrine was written. It was here that the reports of all the base men and the action reports from all of the anti-submarine forces could be collected, correlated, and studied statistically. It was here that a centralized contact could be maintained with the NDRC laboratories and with the laboratories of the Navy. In Washington, detailed theoretical analyses could be worked out and the results sent out to base men who were usually too busy to work out long and complex calculations. Here, the correlated results from all the far-flung bases could be transmitted back to the field so that the man in one locality could see how his colleagues in other areas were doing. Here, supervision of the work could be given by proper Naval authorities, clearances could be had most quickly, authority could best be obtained for publication and distribution, and the general terms of reference of the group with the related services could be maintained.

The makeup of the Washington office was at first preponderately statistical, but as the rotation system began to show returns and the base men began to come back from their first tours of duty, a greater percentage of men trained in

the physical sciences could be maintained in Washington. By that time the group had become balanced and matured.

Aircraft Operations.

The First Bomber Command, AAF, with headquarters at 90 Church Street, New York, supplied long-range bombers for anti-submarine patrol. The commanding officer was Brigadier General Westside T. Larson. Several members of Group M, including Dr. Shockley, visited a number of the First Bomber Command airfields in order to learn at first hand concerning the problems of the Army in anti-submarine warfare.

It was about this time that it was realized that search radar installed on aircraft would be of considerable importance in locating surfaced submarines by day as well as by night. This method of search had enlisted the special interest of Dr. E. L. Bowles, scientific consultant to the Secretary of War. As the result of studies made by the Group, it was indicated that average ranges of first sightings of submarines by radar were definitely larger than average ranges of first visual sightings.

Through Dr. Bowles the group came in contact with Brig. General H. M. McClelland, Director of Technical Services of the AAF, whose field of interest included the AAF's radar problems. Group M derived considerable benefit from the experience of his staff, in particular Dr. Dale Corson who had worked at Radiation Laboratory.

One of the major developments of the summer of 1942 was the establishment of a Sea Search Attach and Development Unit (SADU) to study the tactical and equipmental problems of anti-submarine operations by aircraft. This unit, which included Mr. H. H. Hennington, Dr. M. E. Bell, and Mr. D. D. Cody, was installed at Langley Field, Virginia, and operated under the direction of Col. W. C. Dolan. Among its activities, the Unit worked on, and was of assistance in getting into service, search radars, searchlights and bomb-sights for anti-submarine aircraft.

During the stay of the SADU group at Langley, its members helped maintain liaison between NDRC laboratories and the development unit. They helped to prepare programs for technical tests and then to write up the reports of the tests. They had devised a series of exercises which would check the proficiency

of crews and gear in low-level bombing such as is used in anti-submarine attacks. Tests were conducted to learn the effectiveness of forward-firing rocket flares, bomb sights, search lights, sonobuoys and other gear used in anti-submarine operations.

In the fall of 1942, the First Bomber Command became Anti-submarine Command (AAFAC). A request came from General Larson for Group M to assign members to work on problems of training and material for the AAFAC staff. In October, Dr. A. A. Brown and Mr. M. E. Ennis, and later Mr. A. W. Brown, were assigned in response to General Larson's request. The group conducted a detailed study of all types of bomb sights, to aid in determining what sight or sights were best for anti-submarine work. Out of this study a number of projects developed looking to the perfection of a suitable anti-submarine sight. Work on the project was conducted at Wright Field and elsewhere. A procedure was evolved to obtain adequate photographic coverage of all anti-submarine attacks and coordinate grids were developed to measure photographs of attacks. Group members accompanied officers of the AAFAC staff on their inspection trips in order to provide specialized advice on the spot.

During the winter of 1942-43 the 18th Squadron, based at Langley Field, was designated a special anti-submarine operational training unit. The Squadron Commander, Lt. Colonel R. W. Finn, requested the aid of ASWORG in setting up a schedule of tactical training. In May 1943 Dr. G. R. Pomerat was assigned to this work. He helped to set up lecture schedules, training flight schedules and standards for bombing exercises.

Mission to England.

Drs. Morse and Shockley had thought for some time that it would be desirable to establish a closer liaison with their opposite members in Great Britain. By the fall of 1942, they felt that they were well enough acquainted with the American anti-submarine problem so that a visit to England could be profitably made. Such a visit was particularly timely because of new problems in the anti-submarine war which had developed as a result of the fall of France and the consequent use by the Germans of the Bay of Biscay ports as U-boat bases.

Dr. Morse and Dr. Shockley arrived in London about the middle of November 1942 and reported to the Naval Attache's office, where they were assigned to Captain T. A. Solberg, head of the Technical Section of the Attache's office. Since Drs.

Morse and Shockley also went over as special OSRD representatives, they reported collaterally to Mr. Bennett Archambault, head of the OSRD London office. Mr. Archambault made arrangements for office space and transportation facilities and was helpful in arranging contacts for the two representatives of Group M.

Many contacts had to be made. The Admiralty had operational responsibility for anti-submarine warfare, routed the convoys, and controlled the destroyer escorts on the British side of the Atlantic. The Admiralty also had operational control over Coastal Command's anti-submarine planes.

A particular problem which required settlement grew out of the fact that the AAFAC squadron of B-24's were the first anti-submarine planes in England to have S-band radar sets. British plans - arrangements for blind landings and so on - were built around the longer wave ASV Mark II sets. Consequently, many complications arose. Further troubles grew out of the fact that the American squadron had been assembled hastily and had not had an opportunity for thorough radar training. Thus the inherent advantages of the S-band radar gear were not immediately realized. Following considerable discussion, the members of the squadron were given extra time for further training and were just about ready to go into action when they transferred again, this time at a base in Casablanca in North Africa. There they subsequently performed much useful work.

Negotiations for closer liaison with the operational research group of the Coastal Command were aided by the presence of Mr. J. P. T. Pearman, a pioneer member of the ORS group, who had earlier in 1942 visited the United States at the time a Coastal Command squadron was sent to this country to assist in anti-submarine work in the Caribbean. Mr. Pearman had spent considerable time in bringing the members of ASWORG up to date on the work of their opposite numbers in Great Britain.

Through Prof. Blackett, Dr. Morse and Col. (now Brigadier General) Schonland, head of the Army Operations Research Group, a visit was also made to the Eighth Bomber Command, U. S. AAF, and to the Army Operations Research Group, assigned to that command. The members of this group under the leadership of Mr. J. M. Harlan were recent arrivals and were busily sorting out their numerous problems.

Upon the return of Dr. Morse to the United States, official approval was given to plans to assign at least two ASWORG men to the United Kingdom to provide liaison with the British Antisubmarine Operations Research work. These representatives of ASWORG were to be assigned to Commander Naval Forces in Europe and would work under the direction of Capt. Solberg. One of the two men, it was planned, would spend most of his time in maintaining liaison with the Coastal Command. The other would spend most of his time at the Admiralty maintaining contact with the Operations Research workers there. The British were warm in their approval of this proposal.

Tenth Fleet.

Toward the close of 1942, evidence of divided authority began to trouble those responsible for the success of the anti-submarine effort. Operating units were scattered among sea frontiers, each of which had its own tactical doctrine planning staff and intelligence organization, and was more or less autonomous. The squadrons of the Anti-submarine Command, AAF, were controlled operationally by the Eastern Sea Frontier. Several squadrons were subsequently sent to Africa where they were under still another operational command. Army squadrons were supplied to the Caribbean Sea Frontier by the First Antilles Air Task Force. Some of the Anti-submarine Command squadrons were assigned to England where they were controlled by the Coastal Command, RAF.

A proposal that all AAF anti-submarine activities be unified under the Anti-submarine Command would have provided a certain unity so far as training and equipment went, but the operational control of the Army planes would still have been divided.

A solution was found by the establishment in May 1943 of the Tenth Fleet with Admiral Ernest J. King as Commander, Tenth Fleet, and Rear Admiral F. S. Low as Chief of Staff.

The division of operational authority which had caused the establishment of the Tenth Fleet had had an adverse effect on the work of Group M. Those assigned to the Army Anti-submarine Command found themselves working on plans for training and material which often differed from Navy plans for naval aircraft. Tactical doctrine differed and there was inevitably a certain amount of rivalry in pushing new equipment developments, thus making for duplication of technical effort. No two sea

frontiers interpreted and used operational doctrine and intelligence in exactly the same manner. Group M members assigned to outlying bases had often found themselves to be the sole agents sufficiently well informed to bring about unified doctrinal planning. Since the function of Group M was technical and analytical rather than operational this sometimes led to embarrassment in command relations.

Lack of unified authority had been particularly hampering to the work of Group M's Washington office. Many of the results of the statistical and analytical studies suggested new operational procedures, yet there had been no central authority to whom suggestions could be reported and who could take action on the suggestions if action was deemed advisable. Thus the establishment of the Tenth Fleet was extremely pleasing and beneficial to Group M and enabled the members of the Group to work with far greater efficiency.

The establishment of the Tenth Fleet was followed during the early part of 1943 by another most helpful development. Debate over the proposal that all Army anti-submarine flying should be unified under the Anti-Submarine Command was settled by a decision that the Navy should gradually take over all anti-submarine activities in the Atlantic, that the squadrons of the Army Air Forces Anti-Submarine Command in England and in Africa should eventually be replaced by Naval squadrons, and that the Anti-Submarine Command should revert to its original status as the First Bomber Command.

This decision simplified the work of Group M and while the transfer to the Navy of all responsibility for anti-submarine warfare was being completed, the activities of Group M which had been connected with the Army's anti-submarine effort were tapered off and its activities at the various Naval bases correspondingly enlarged. In August 1943, the ASWORG unit at Langley Field was closed down and the men who had been assigned to AAFAC headquarters in New York were given other assignments.

Meanwhile Group M was made an official part of the Tenth Fleet and at last occupied that central position and enjoyed that direct contact with the highest operational authority, which its members had so long desired.

Still another important development was the formation in February 1945 of the Air Antisubmarine Development Detachment, Atlantic Fleet (AirAsDevLant). This unit, under Commander Air Forces, Atlantic Fleet, and combining the activities of the tactical development unit and the specialist training unit, filled a long-felt need for an organization which would carry on tactical experimental work in antisubmarine operations and which would at the same time provide operational training for antisubmarine air crews. The commanding officer of the detachment was Capt. Vosseller who had been connected with the early development work of ASWORG. The unit was located at Quonset Point, Rhode Island.

In response to a request for technical help Drs. C. F. Squire and W. J. Horvath, were assigned first to the unit and later Dr. Bell was transferred there the next July.

The ASWORG unit at Quonset worked on a great variety of problems. They helped to devise tactical and operational tests of new equipment, and to write the manuals and tables to govern its use. They helped test various types of new low-altitude bombsights. They made calculations for proper sighting and intervalometer settings for glide bombing. They devised procedures for the testing of rockets, and devised and analyzed a variety of tests having to do with visual and radar sighting. They helped in the establishment of methods for the effective utilization of sonobuoys and investigated the proper tactics for searchlight planes. In July the responsibilities of the Air Antisubmarine Development Detachment were broadened to include tactical experimental work with surface craft. The "Air" was dropped from the unit's title and it became the Antisubmarine Development Detachment (AsDevLant). The original Group M unit became the Aircraft Division of the new detachment and a new co-equal Surface Division was added. Dr. R. M. Elliott was assigned to the Surface Division and assisted Commander H. R. Hummer, section head, in testing various sonic and other detection gear. Mr. J. K. Tyson was also assigned to the Surface Division which he aided by analyzing trials of surface vessel attack procedure.

The inauguration of the carrier escort group as a major factor in antisubmarine warfare confronted Group M with a set of new problems. In order to study these problems at first hand Dr. W. E. Albertson was sent on an operational trip.

Pro-Submarine Activities.

By the fall of 1943 Group M had grown to approximately 50 members and it began to be apparent that operational research could be of use to the Navy in studying other than anti-submarine problems. A first broadening of interest was in the direction of aiding our own submarines. Dr. Tate and Mr. T. E. Shea visited Pearl Harbor and discussed matters with Commander Submarines, Pacific Fleet (ComSubPac). Shortly thereafter a request came from Pearl Harbor for the assignment of several ASWORG members to assist the ComSubPac staff. In answer to the request, Drs. G. E. Kimball and R. F. Rinehart were sent to Pearl Harbor, Dr. Kimball to return after a short visit, Dr. Rinehart to stay on indefinitely. Subsequently, four other Group M members were sent to work under Dr. Rinehart, and a complete IBM installation was set up at Pearl Harbor. Under Dr. Charles Kittel, a corresponding pro-submarine group was set up at Washington to work on statistical and analytical problems.

During 1944 still other requests for members of Group M came in from Naval units in the Pacific. Vice Admiral T. C. Kincaid, Commander Seventh Fleet in the Southwest Pacific Area, requested an anti-submarine analyst for his staff. Dr. Steinhardt was moved from his assignment with the Fourth Fleet in Brazil and was sent to Brisbane, Australia, and later to Manus (Admiralty Island), in March 1944. Subsequently, he was replaced by Mr. A. M. Thorndike. In June Mr. R. E. Traber was sent to Pearl Harbor to work with the Anti-Submarine Training Unit in Fleet Airwing Two. He was later replaced by Mr. Gordon Shellard.

In the meantime, a new unit of OSRD, the Office of Field Service, had been established and ASWORG transferred to it, although it continued to operate as an integral unit, and completely under Cominch control, most members of the staff having been transferred in January 1944. From that time on, Group M was not strictly a part of Division 6, though the relationship between group and division remained practically as close as before.

In October 1944, the entire Group M was transferred back to Readiness Division of Cominch and was reconstituted as ORG, a part of the Research and Development Section with Dr. Morse as Director. ASWORG became a sub-group assigned back to Tenth Fleet, and other sub-groups were formally organized and

assigned to the appropriate parts of the Cominch Staff, Chief of Naval Operations, or to the Fleet Commands. The group had won final recognition as an integral part of the Naval Staff organization.

Types of Operational Research.

Operational research falls naturally into three principal categories: Statistical, Analytical and Materiel.

The statistical part of operational research consists of the collection and statistical analysis of operational data, particularly data derived from action reports. The more detailed the data concerning the success or failure of the action, the more useful will be the analysis; for the aim of statistical studies in operational research is not to provide a history of the past but to determine how practical doctrine can be modified to provide a more effective type of operation in the future.

The goal of the analytical part of operational research is to work out theoretically the best tactics to use in a new situation. The theory is derived from a combination of knowledge concerning part operations and specialized knowledge concerning the behavior of equipment.

That part of operational research concerned with materiel is itself divided into two parts. The first consists of the detailed study of the characteristics of new apparatus in order to indicate in advance its most effective employment in operation. The second is the detailed study of the behavior of equipment in action in order to recommend possible modifications in design or development of new equipment.

In practice, of course, no hard and fast line can be drawn between these categories. There are many overlappings and most problems studied by Group M had their statistical, analytical and materiel aspects.

The results of Group M's studies were published in a variety of forms. By 31 August 1944, the list of Group M publications included: 45 memoranda, 52 articles in the Navy's Anti-submarine Bulletin, 22 inter-office bulletins and 64 research reports.

The reconstitution of the group as ORG in the Readiness Division resulted in a natural expansion of the report system.

Four general categories were set up: (a) Memoranda, which were the results of short studies usually in response to specific requests and ordinarily were distributed only to the person or persons making the request: (b) Studies, which were reports on research involving more than one or two man-days of work, and which normally had only a limited circulation outside the group; (c) ORG reports or publications, which meant that when a study received widespread approval from the group and when requests for it resulted in a fairly widespread distribution, after editing and approval, it was reissued as an ORG report or publication; (d) Contributions, which were portions of studies which sometimes appeared in the form of articles in some official Naval publication.

Punch Cards.

Analyses, made possible through the use of punch cards and IBM machines were most helpful in measuring the efficiency of tactics and of gear. Eastern Sea Frontier provided many of the data which went onto the punch cards. Each plane on returning from an anti-submarine patrol filled out a form which gave the details of the mission and the details of any sightings, visibility, and so on.

In the securing and the analysis of data from anti-submarine action reports and the preparation of situation submarines, the members of Group M came to depend upon Commander (now Captain) R. P. Collins. His understanding cooperation saved the group from many false starts. In the devising of punch cards and the designing of codes certain members of the group played important parts. Among these were Professor Wilks and Messrs. W. L. DeVries, H. H. Hennington, P. J. McCarthy and later Mr. R. R. Seeber, and Mr. Earl Gardner.

As the work of Group M progressed, the card files grew. In addition to the ships' casualty files of the world-wide assessment files, there were files giving details concerning attacks on enemy submarines by U. S. surface and aircraft and on convoys. Another file was based on action reports of our own submarines in the Pacific and another on air actions in the Pacific.

Determination of the probability of success in depth-charge patterns led to the punching of 7,500 cards giving error distribution based on operational statistics covering

results of all types of patterns. In a similar manner, a file of 7,000 punch cards was built up to compute the probability of success for surface vessel search plans. From all these studies came conclusions that were embodied in later improved procedure.

Countering the Acoustic Torpedo .

One of the most important countermeasure problems dealt with by Group M was that of finding means to combat the German acoustic homing torpedo. In 1943 rumors began to spring up that the Germans were preparing to use a torpedo which steered toward the noise of a ship. Soon the rumors were confirmed by prisoner of war statements. In the fall of 1943 the torpedo appeared.

Thanks to the advance warning, Group M was already prepared with a number of countermeasures. This part of the program was placed under the direction of Dr. E. A. Uehling.

The problem was not a simple one. Out of their technical knowledge the scientists had to estimate just how the torpedo was controlled. A countermeasure effective against a torpedo of one type might be ineffective against a torpedo with other physical properties and might actually increase the danger from torpedoes with still other characteristics. To be effective, a countermeasure had to be based upon knowledge of how the torpedo would respond to intensity changes, how selective it was in frequency, and whether it could hear sounds from all directions or only from ahead.

A large number of typical pursuit curves were computed for torpedoes with varying properties. The torpedo experts of Division 6 were canvassed for their opinion as to what properties the homing torpedo might have. These opinions, coupled with prisoner of war statements, narrowed the probable selection down to two or three types. An attempt was then made to find a countermeasure which would be effective against all or nearly all of these types.

CHAPTER VII

SUBMARINE SEARCH PROCEDURE

The problem of determining the proper methods of search for submarines entered into more than half of the anti-submarine tactics and into a great deal of naval tactics in other fields. This problem, therefore, occupied much of the attention and required the expenditure of considerable energy on the part of Group M.

The ocean is wide and it is impossible to watch all parts of it all of the time. The alternative is to watch some parts of it some of the time, not casually, but in conformity with a carefully devised procedure built upon an analysis of all the essential factors.

Basis of Search Plans.

In considering search plans, one of the first factors which must be taken into account is the range of detection, whether it be by eye, by radar, or by sonar gear. At first the simplest possible assumption was made, that is that nothing was detected outside the range of detection, while everything was detected which came within the range. It was soon recognized that this simple assumption of a sharply limited search range was a very crude approximation. Actually, some surfaced submarines are seen at great distances by aircraft, and others under the same conditions, are not seen until close in.

It was necessary, therefore, in studying the search problems, to calculate the probability that a submarine might be seen at a given range. From this probability one can then compute the average range under which the submarine will be detected under certain conditions.

More important than the range of detection is the search rate, that is the rate at which a craft with its detection gear can search over the ocean for the enemy submarine or surface vessel. In order to compute the number of square

miles which a given craft could search over in an hour, again a simple first assumption was made; that this rate of search was equal to the speed of the craft multiplied by twice the range of detection for the gear in question. The rate of search varies widely with type of craft and from craft to craft.

As work on the search problem proceeded, it was found that fears concerning the inadequacy of operational reports were well founded. It had been hoped that empirical curves for the probability of sighting could be computed from the operational data. But it was discovered that many reports did not give both elevation and visibility and the reports which did were not numerous enough to provide a solid basis for computations. There was an even more fundamental difficulty. The reports were confined to sightings which resulted in attacks. There were no corresponding reports sent in on sightings which did not result in attacks. There was good reason to believe that these latter sightings were often the long range sightings and their absence resulted in a one-sided set of facts.

The research workers, however, went ahead with their problem and gathered such data as they could. From the Eastern Sea Frontier and from the Bay of Biscay area, data were obtained giving the total number of hours flown by the planes and the total number of sightings of all sorts obtained. In these areas it was possible to estimate with reasonable accuracy the number of submarines present at a given time, and by also estimating their submergence tactics, one could estimate the average number of submarines which could be sighted by planes in the area. From these data an estimated search rate was obtained for both the Eastern Sea Frontier and the Bay of Biscay area.

Then came a somewhat dismaying revelation. The estimated effective search rate turned out to be from 1/3 to as little as 1/20 of that computed by using the average range of vision times the speed of the plane. The discrepancy was too great to be explained away by ascribing it to inadequate data, or errors of computation. One explanation was inefficiency in our own search tactics, but part had to be due to the fact that many submarines which should have been seen were not seen. Admittedly rough, as these results of the first search studies were, they pointed to the great necessity of obtaining more complete data on sightings, for without them

one could never be sure how tight various barrier patrol plans actually were.

In order that more data could be obtained from England covering sightings in the Bay of Biscay, Coastal Command consented to allow Dr. A. F. Kip to make a study of data collected by the various anti-submarine air bases. Dr. Kip collected and sent to Washington a sample of 529 sightings with all the pertinent data concerning altitude of planes, meteorological visibility, range and bearing of first sighting, and so on. In Washington, the material was put on punch cards and analyzed statistically by Dr. G. E. Kimball who was responsible for many of the theoretical developments in this field.

This statistical analysis showed how the average range of first sighting was related to the prevailing conditions. One further step was necessary before this empirical information could be satisfactorily linked with fundamental theory, to connect it with the physiological properties of the human eye for visual search. This step was taken by Dr. E. S. Lamar, who went to London and discussed the interpretation of the British data with the members of Coastal Command's Operational Research Group. Through them he was able to obtain physiological data from the measurements of Craik and Macpherson of the British Medical Research Council. This fundamental problem has been more recently explored by Dr. Lamar in cooperation with Professor Selig Hecht of Columbia University.

As a result of these studies, it was shown that there was a certain maximum range of vision for any given object, and the dependence of this range on various factors was worked out. The more complete theory extended to much smaller sized objects, such as life rafts, periscopes and the like. Thus as the result of the work of ORG, it can be said that the main aspect of the fundamental problem of visual search for and sighting of an object on the ocean from an airplane has been solved.

CHAPTER VIII

TACTICAL-TECHNICAL INTERPLAY IN THE ANTI-SUBMARINE WAR*

The second time within a generation in which the United States found itself involved in a war in Europe saw our fortunes again bound up with those of Great Britain. As in World War I, World War II found us committed to the support of this ally whose ability to contain the Germans on the west constituted our eastern first line of defense. Thus, we had to supply the British Isles, and as the war progressed and we pushed our offensive toward Europe, we had to supply the forces we had advanced into the United Kingdom, Africa, Italy, and finally France and Germany.

The Logistical Problem.

The anti-submarine war was primarily a war to keep secure the transatlantic routes of supply. As such, it posed the following logistical problem:

Great Britain has customarily maintained afloat approximately 20,000,000 gross tons of merchant shipping consisting of some 2,500 ocean-going vessels of 6,500 gross-tons average and an equal number of coastal ships of 1,200 gross-tons average. In the past two wars in which Great Britain has had the United States as one of her allies, those allies plus friendly neutrals have had available another 20,000,000 gross tons of shipping.

Cut off from Europe, the United Kingdom at war must depend primarily on transatlantic supplies in order to exist. In 1943, the total imports to the United Kingdom averaged approximately 3,600,000 long tons a month, more than 80 per cent of this tonnage being carried by the North Atlantic convoy system.

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*This chapter is based almost entirely on a report entitled "Anti-Submarine Warfare in World War II," prepared by the Operational Evaluation Group (Report 51, Part I) of the Navy Department, used by permission of the U. S. Navy Department.

The average ship in a North Atlantic convoy took about 70 days to make a round trip, half the time being spent at sea and half in port. This average ship of 6,500 gross tons could carry about 8,000 long tons per trip. Thus it took in 1943 a fleet of between 7,000,000 and 10,000,000 gross tons merely to keep the United Kingdom fed and supplied.

But we sent to Europe an Army, every soldier of which required the transportation of some 5 tons of equipment and supplies when he went, and an additional ton for every month he remained. Since complete replacements were needed on the average once each year, that meant between 16 and 20 long tons to maintain one soldier for a year, or 3 to 5 gross tons of shipping which must always be available if he were to be constantly supplied; in other words, a fleet of 20,000,000 gross tons continually plying the Atlantic in order to keep 5,000,000 men in Europe.

This was the logistical equation which had to be solved with respect to the European and Mediterranean theatres. In addition - though the Japanese threat to our ocean transportation was only a fraction of that on the other side of the world - we still had many hundreds of thousands of soldiers and sailors and marines in the Pacific who had also to be supplied by sea with food and the tools of war, and over routes far longer than those of the Atlantic.

The war against the U-boat, of which the Battle of the Atlantic was the major action, illustrated, as did perhaps no other phase of World War II, how close - in this era of science and scientific weapons - is the interplay between the experimentation of the research worker in his laboratory and the tactical planning of the military leader in his theatre of operations.

The anti-submarine war divides itself naturally into a number of chronological periods each marked by a typical homogeneity of U-boat strategy and tactics and of Allied countermeasures.

Period I.

Period I extended from the beginning of the war through June 1940.

The German invasion of Poland, 1 September 1939, which marked the outbreak of World War II, found the Germans with

only 30 ocean-going submarines, 20 of 500 tons and 10 of 750 tons.

But if the number of German U-boats was small, so was the number of anti-submarine craft available to the British - only some 165 destroyers, 35 small patrol craft and 20 trawlers fitted with ASDIC devices. France had 59 destroyers. By comparison, more than 3,000 vessels, including some 900 destroyers and 170 patrol craft, had been available to the Allies for anti-submarine warfare in 1918.

Despite the shortage of escort vessels, the British profited by their World War I experience and immediately adopted the convoy system. The Germans, however, were able to find numerous vessels sailing independently and merchant ships began to be sunk at a dismaying rate.

Shore-based aircraft of the British Coastal Command shared in the defense against the U-boats. Though ineffective in attack, they did tend to keep the U-boats submerged.

In October 1939, Prien, commander of U-47, penetrated Scapa Flow and sank the battleship HMS ROYAL OAK - a disaster to the British which had one fortunate aspect in that it brought home the need of protecting harbors against submarine attack by means of underwater sound equipment.

June 1940, closing month of Period I, was a dark month for the Allies. Allied shipping losses to U-boats rose to 56 ships of 267,000 gross tons, France fell; Italy entered the war with more than 100 submarines, of which some 60 were ocean-going.

As assessment of the events during the ten months of Period I in the U-boat war showed that on the whole the convoy system was effective. Some 2500 ships a month had been convoyed with losses to U-boats of ships in convoy of only 5 per month. Merchant vessels not in convoy were sunk by U-boats at a rate four times as high.

On the debit side of the Allied ledger, however, shipping losses of the allied and neutral nations from all causes amounted to 280,000 gross tons per month of which 223,000 gross tons were due to enemy action, 106,000 gross tons being losses to U-boats.

Period II.

Period II lasted from the beginning of July 1940 through March 1941.

During Period I Allied patrol planes had achieved considerable success in forcing U-boats during daylight to travel below the surface where they could be detected and tracked by ASDIC-fitted surface vessels. The resulting short life-expectancy of their U-boats forced the Germans in Period II to adopt a complete change of tactics.

They abandoned the method of attacking from periscope depth during daylight. Instead, Period II saw U-boat commanders switch to surface attacks at night. Trimmed down on the surface, the U-boats launched their torpedoes under cover of darkness, then used their comparatively high surface speed to escape. The period was also distinguished by the successful raids of such submarine "aces" as Prien, Kretschmer and Schepke. Initially, at least, the modified tactics of the enemy were highly successful.

The Allied anti-submarine defense had also to contend with another problem. The fall of France permitted the Germans to use the French ports. Thus they were able to extend the westward range of their U-boats, while occupancy of French airfields made it possible for them to send out long-range aircraft to spot approaching convoys. Allied merchant vessels were compelled to take a longer route around the north of England.

Another disadvantage suffered by the Allies was that this was the period when an invasion of England appeared possible and ships and planes heretofore available for escort and anti-submarine patrol work had to be assigned to defensive stations to guard the south and east coasts of the British Isles. Furthermore, Italian submarines joined the Germans in the Atlantic.

Allied countermeasures were stepped up. New systems of evasive tactics for convoys were devised. Patrol planes were fitted to carry depth charges. British aircraft launched punishing attacks on U-boat bases in the French ports of Lorient and Bordeaux.

British scientists produced a helpful countermeasure in an improved H/F D/F, or High Frequency Direction Finder, a

device which picked up radio signals from a U-boat while it was transmitting by wireless and indicated the U-boat's direction. Installed at first at shore stations and later on escort vessels, H/F D/F proved most helpful in giving warning of a submarine in the vicinity. Two or more sets of the device could be used, by triangulation, to locate the general position of a U-boat.

Also, late in 1940, radar began to be installed, first on ships, then on aircraft. Radar enabled the bearing and range of the target to be determined, even at night or during conditions of poor visibility.

During the nine months of Period II, 23 German U-boats were sunk or probably sunk in the Atlantic and eleven Italian submarines in the Mediterranean.

To offset these losses, the Germans had commissioned about 45 new submarines, giving them an estimated 54 U-boats available at the close of the period, or about twice the number they had at its beginning. Despite the greater allied anti-submarine effort, the average life of a U-boat at sea had risen from the three months of Period I to four months, and the average U-boat sank per month 4 ships of 22,000 gross tons, a slight increase in tonnage over the previous period. The merchant ship U-boat exchange rate, however, had swung slightly in the former's favor with 16 ships of 88,000 gross tons sunk for every U-boat sunk or probably sunk.

From the point of view of available shipping, the Allies were deeper than ever in the red. Total shipping losses of 456,000 gross tons per month represented an increase of nearly 60 per cent over the first period. The building rate of ships had increased to only 114,000 gross tons per month, so that the net loss brought total shipping available down from about 38,000,000 gross tons at the start of the period to about 35,000,000 gross tons at the period's end.

The British anti-submarine fleet received an important addition during the period. In return for the right to lease bases in British Western Hemisphere territory like Newfoundland, Bermuda and Trinidad, the United States transferred to the British fifty old-type destroyers.

Period III .

April 1941, when the sub-surface warfare group of NDRC was just getting under way, marked the beginning of the U-boat war's third period, which was to last until December 1941.

Once again, Allied countermeasures had forced the Germans to switch tactics and Period III saw a shift from the close surface attack by one or two U-boats in favor of the "wolf pack" system, in which a U-boat encountering a convoy withheld its attack until it could summon other submarines in the vicinity for an attack in unison.

One reason for the change in tactics was the increasing effectiveness of Allied escort vessels equipped with the High Frequency Direction Finder and radar.

Another reason for the adoption of the "wolf pack" system was that, because of deaths due to Allied action and to the expansion of the U-boat fleet, seasoned submarine officers and men were being spread thinner and thinner. The "wolf pack" attack in concert enabled less experienced U-boat crews to be guided by their more experienced colleagues.

April 1941 opened with an attack which was to be typical of the next 9 months, when five U-boats combined forces to raid convoy SE-26 before its escort had joined up. Ten ships of the convoy, including an armed merchant vessel, were sunk.

U-boats began pushing the principal areas of their attacks farther southward and westward to the Azores and Freetown area. June 1941 saw the area of attacks still spreading with U-boats raiding off Newfoundland and south of Greenland. The U-boats' score for the month was 57 ships of 296,000 gross tons. During the month, however, 5 U-boats were sunk.

The spread of the U-boat war caused President Roosevelt to announce in July 1941 that the safety of the United States required the basing of American anti-submarine forces in Iceland. The Allies reached a decision that the only means of safeguarding convoys was to provide an escort clear across the Atlantic, even though this meant diminishing the number of escort vessels which could be assigned to each convoy.

The Allies could find some satisfaction in statistics. In September 1940, with an average of only 7 U-boats at sea,

the Germans had sunk Allied and neutral merchant ships at an average rate of 300,000 gross tons per month. A year later, in September 1941, with an average of 35 U-boats at sea, ship sinkings were running only some 200,000 gross tons per month.

September 1941 was noteworthy because of the declaration by the United States that it would give protection to all ships carrying lend-lease materials, regardless of a ship's nationality. On 16 September, convoy HX-150 sailed from Halifax with warships of the United States Navy appearing for the first time among the excort vessels.

During November 1941 only 12 ships of 62,000 gross tons were sunk by U-boats. In part at least, this comparatively low rate of sinkings was due to the work of the British Coastal Command whose aircraft made U-boat commanders prefer to stay outside their patrol range, some 400 miles off shore. Experience in the evasive routing of convoys was also paying off. Another contributing factor was, of course, the British offensive in Libya, which caused the Germans to divert some of their submarines from the Atlantic to the Mediterranean.

December 1941 found the United States thrust into the war by the Japanese attack on Pearl Harbor. Between 7 December and the end of the month Japanese submarines sank 9 Allied ships of 42,000 gross tons. On the other side of the world, the figures of shipping losses remained fairly favorable. In the Atlantic, 10 ships of 50,000 gross tons were sunk and in the Mediterranean, 7 ships of 27,000 tons. The enemy, however, did not achieve these successes without cost to himself. Five U-boats were sunk in the Mediterranean and in one attack by six U-boats on convoy HG-76, four of the attacking submarines were sunk, though at the loss of 2 merchant ships, one escort vessel, and HMS AUDACITY, the first British escort carrier.

Period III was notable for a number of technical innovations.

In July CAM ships were introduced. These were merchant ships equipped with fighter aircraft launched from catapults. Allied aircraft were provided with more effective armament for anti-submarine attacks.

Aircraft patrols over the Bay of Biscay were intensified and had the effect of forcing the U-boats to run submerged in

their transit to and from the French ports, thus increasing their transit time and correspondingly decreasing the time they could remain at sea. Another technical innovation was the adoption by the British of the "hedgehog," a multiple-spigot mortar mounted on the fore part of an escort ship, which could forward-fire a pattern of bombs armed to explode on contact.

Notable advances in the use of radar were also made during the period. Not only was greater experience with the gear bringing in good results, but a new set, Type 271, was devised by the British and was being fitted on their corvettes. This was a short wave (10 centimeter) beam-type device and constituted a great advance in radar for anti-submarine purposes.

During the period a total of 44 enemy submarines were sunk - 22 German and 8 Italian submarines in the Atlantic, 6 German and 7 Italian submarines in the Mediterranean, and 1 Japanese submarine in the Pacific.

Despite these losses, the fruits of the intensified German U-boat construction program were beginning to appear. At the start of the period, with approximately 54 U-boats available, the Germans were able to keep about 18 at sea in the Atlantic at all times. By the close of the period, the number of available U-boats had risen to approximately 200 and the average number in the Atlantic at any one time was about 36.

At the same time, the effectiveness and efficiency of U-boat operations showed a sharp drop. Despite the increase in the average number of U-boats at sea, they were able to sink only about 34 ships of 166,000 gross tons per month in the Atlantic during Period III, or about 25 per cent less than during Period II. This meant that the average U-boat was sinking only one ship of about 5,000 gross tons per month at sea and was therefore only about one-fourth as effective as in the previous period. Obviously, the loss in efficiency was due only in part to the success of Allied tactics, and proved that the U-boat fleet could not be expanded as rapidly as it had been without suffering from the use of comparatively inexperienced personnel.

The Allied shipping position during Period III showed some improvement. Although losses averaged 363,000 gross tons

per month, as against 175,000 gross tons of new construction the net loss of 188,000 gross tons per month was 45 per cent less than during the previous period. Despite this hopeful sign, total net losses for the period brought shipping available to the Allies down to 33,000,000 gross tons at the period's close.

The anti-submarine escort vessel situation showed improvement. British ocean-going escort had risen in number from 375 to approximately 500, and the entry of the United States into the war added 175 destroyers to the number of available escorts.

Period IV: Through September 1942.

Period IV of the anti-submarine war, from January 1942 to September 1942, found the U-boats extending their range to the very shores of the latest principal participant - the United States.

During the 9 months of Period IV the U-boats sank 878 Allied and neutral vessels of 4,587,000 gross tons, which meant that losses from U-boats averaged 98 ships of 510,000 gross tons per month. The world-wide total of enemy submarines sunk during the period was 78, making the exchange rate 11 merchant ships of 59,000 gross tons sunk by U-boats for each U-boat sunk.

During the period, Japanese submarines sank 76 ships, 48 in the Indian Ocean and 28 in the Pacific. Japanese submarine losses were 11, or an exchange rate of 7 merchant ships sunk to one submarine lost. In the Barents Sea, on the northerly convoy route to Russia, 15 merchant vessels were lost as against 2 U-boats sunk. The Mediterranean was the only area in which the rate of exchange favored the Allies. There, 21 enemy submarines were lost and only 17 merchant ships were sunk.

But the principal area of battle during Period IV was the Atlantic, where almost 90 per cent of the Allied shipping losses occurred and where an average of 57 U-boats at sea sank a monthly average of 85 ships of 456,000 gross tons. During this period the average U-boat at sea sank one and a half vessels of 8,000 gross tons per month, or 50 per month more than during the previous period.

U-boats in the Atlantic during this critical phase of the war were safer than at any other time. Of the average of 57 submarines at sea, four and a half were sunk per month so that the U-boat's average life attained a high of 13 months, during which it could be expected to sink 19 ships totaling 100,000 gross tons.

The U-boats achieved these successes by concentrating their raids in the United States Strategical Area, where, at that stage of the war, the defenses were weak and shipping unescorted. In the area, the Germans maintained 37 out of the average of 57 U-boats at sea, and these 37 submarines sank an average of 75 ships of 375,000 gross tons per month at a loss to themselves of only 2 1/3 U-boats per month. By September 1942, the Germans were able to maintain as high as 93 U-boats at sea in the Atlantic at any one time. In addition, they were able to maintain an average of 20 U-boats in the Mediterranean and another 20 were available for operation in the Barents Sea. Japan had approximately 75 submarines available and operating in the Pacific and Indian Oceans.

So serious were the losses in the U. S. Strategical Area, that in March the United States was forced to convoy shipping along the East Coast. This coastal convoy system required the marshalling of all our available forces. The Navy assigned to the job every available plane and blimp, and was lent assistance by first one and then a second Army air unit. In order to conserve anti-submarine forces, all forces of this type, of the United States, Britain and Canada, were consolidated into a single transatlantic convoy escort system.

During May, the situation in the Gulf Sea Frontier became particularly serious. The average number of U-boats in that area was estimated at only 4, but during the month they sank 41 vessels of 220,000 tons - probably an all time high for sinkings by U-boats in any area during any period of the war. At the rate of sinkings prevailing in the Gulf during May, the life expectancy of a merchant vessel at sea in that area was only 2 months.

The increased number of U-boats available to the Germans was beginning to tell. By August, 1942, while still continuing their attacks in the U. S. Strategical Area, the Germans were able to resume raids in the North Atlantic.

On the other side of the ledger, however, toward the close of Period IV, Allied aircraft were beginning to prove themselves more and more important as detectors and attackers of U-boats. Allied planes were equipped with improved depth bombs filled with charges of a new higher explosive. Still more intensive patrolling of the Bay of Biscay was undertaken. Radar and searchlights permitted Allied aircraft to extend their patrolling into the night with excellent effect, though German technicians scored by developing a search receiver which could detect transmission from Allied radar sets then in use.

Also, on the more optimistic side of the ledger was the fact that Allied antisubmarine craft had been increased from 670 to 745, including 60 new destroyers and 12 auxiliary aircraft carriers. The United States naval building program included approximately 500 new escort vessels, of which about half were destroyer escorts.

Another favorable factor was the tremendous gain in the construction of merchant vessels, particularly on the part of the United States, where the efforts of the Navy, the Maritime Commission, the War Shipping Administration and the American shipbuilding industry had pushed the rate of construction up from 100,000 gross tons in January 1942 to 700,000 gross tons in September of that year.

Period V: Through June 1943.

The nine-month period from October 1942 through June 1943 marked the turning point in the war against the U-boat.

The period's beginning saw the enemy submarines, driven from American coastal waters, intensify their wolf pack tactics against Allied shipping in the Atlantic. The early months of the period saw Allied shipping losses mount to a new all-time high. But before this period of the war was over, intensified Allied countermeasures and production had turned the tide against the submarine.

Allied aircraft came into their own as an offensive weapon against undersea raiders. American and British scientists and technical experts forged so far ahead of the scientists of the Axis that Admiral Doenitz shook up the whole German system of technical development of submarine devices. For the first time during the war, new construction of shipping, particularly

in the United States, attained a rate of production exceeding the rate of shipping loss and for the first time, the Allies were able to conclude a period with a greater tonnage of available shipping than at the period's start.

During a major part of Period V an average of more than 100 U. boats were at sea. Their number was so great that while concentrating against the all-important Allied convoys in the Northwest Atlantic, they were able at the same time to conduct campaigns against shipping in the Caribbean, Brazil, Freetown and Southeast Atlantic areas.

October 1942 saw 93 ships of 614,000 gross tons fall victim to the U-boats. U-boats in the Northwest Atlantic area alone rose to an average of 22 during the month. Their attacks were in the mid-ocean gap beyond the range of land-based Allied aircraft. Another group of U-boats, operating between Natal and Dakar, forced the Allies to route South Atlantic shipping via the Panama Canal and Cape Horn to Capetown. This created a new soft spot on which two packs of 6 U-boats quickly capitalized. In the Capetown and South Indian Ocean areas, they sank 25 ships during the month.

Another U-boat concentration centered east of the Azores and Madeira. Sensing that an invasion of North Africa was in the making, but fortunately failing to guess the exact points of assault, the Germans attempted to lie in wait for the invading armada. In this they failed. The ships of the invasion were able to pass through a concentration of between 30 and 40 U-boats and reached Gibraltar with no losses while troops were aboard, though the invasion fleet was mauled on its return journey. Losses incident to the invasion totalled only 134,000 gross tons, of which 84,000 tons of shipping and 6 naval vessels were lost as a result of U-boat attacks.

The situation grew worse in November 1942, when world-wide losses of shipping from all causes reached the war's high point of 862,000 tons, of which losses from U-boats accounted for 116 ships of 712,000 gross tons.

The Allies made frantic attempts to step up their countermeasures. In December 1942 sinkings by U-boats fell to 62 ships of 344,000 tons and in January 1943 to 34 ships of 203,000 gross tons. But bad weather had much to do with the lower losses, and the Allies were not deluded into believing that the U-boat menace had disappeared. Evidence that the Allies' apprehensions were fully warranted was the fate of

Convoy TM-1. Consisting of 9 tankers and 4 escort vessels, bound from Trinidad to Gibralter, the convoy lost 7 of its tankers to U-boats while out of range of shore-based aircraft. It was becoming more and more apparent that defeat of the U-boats could not be achieved until virtually uninterrupted air cover for convoys was provided.

February 1943, with losses from U-boats totaling 63 vessels of 359,000 tons, proved that the December and January lull had only been temporary. Approximately half of the Atlantic losses were in the northwest area, where wolfpacks of 20 U-boats and more were in action. As a countermeasure VLR (Very Long Range) aircraft began operations during the month in an effort to provide air cover over the gap.

March 1943 saw world-wide losses from U-boat attacks totaling 107 vessels of 627,000 gross tons. U-boat packs were frequently outnumbering escort vessels two to one. On one occasion, Convoys HX-229 and SC-122, which were routed closely together, ran into a pack of 40 U-boats and in the ensuing action lost 20 ships. VLR's finally were able to come to the rescue and force the U-boats to retire. This was on 20 March, a date which is sometimes referred to as the decisive date in the antisubmarine war, since thereafter increasingly energetic Allied measures succeeded more and more in blunting the offensive power of the enemy, and losses of merchant vessels declined at an ever increasing rate.

It was during March 1943 that the USS BOGUE, first United States escort carrier, started to operate in the North Atlantic. Also in that month it was agreed that starting in May the United Kingdom and Canada should be responsible for the security of convoys across the North Atlantic, with the United States providing certain air and sea forces.

Shipping losses from U-boats in April 1943 fell to 56 ships of 328,000 gross tons, with losses in the Northwest Atlantic only half of what they were in March. Japanese submarines sank 6 ships in the Southwest Pacific off the east coast of Australia. The month saw 17 U-boats sunk in the Atlantic for a record high to that date. Five antisubmarine "killer groups" were in action in the North Atlantic, two of them with their own escort carriers. These groups had as their mission the destruction of U-boats and were not tied down to convoy duty.

May 1943 was a crucial month. Some 120 U-boats were at sea in the Atlantic, and a decisive battle took place on 4 May between Convoy ONS-5 and a pack of about 40 U-boats. The convoy consisted of some 30 ships and 4 stragglers. An escort of 6 escort vessels was present during the engagement. During the afternoon of 4 May, despite bad weather, aircraft of the RCAF carried out two attacks, one of them which sank one of the U-boats. Shortly after midnight, two U-boats launched major attacks and sank 12 ships. On 5 May, due to bad weather, air cover could be provided for only a brief time, but after midnight the weather cleared and from then on the escorts had the upper hand. During the course of the night they repulsed about twenty-four attacks by U-boats without sustaining any losses and at the same time inflicted severe losses on the enemy, at least 5 U-boats being considered sunk.

After 17 May no ship was lost in the Atlantic north of 45 degrees north latitude. World-wide losses to U-boats in May increased to 50 ships of 275,000 gross tons. The number of U-boats sunk during the month reached a record high of 41, with 38 of the sinkings in the Atlantic. Shore-based aircraft accounted for more than half of the U-boats sunk during the month, while carrier-based aircraft participated in three of the attacks in which the submarine was considered to have been sunk. By the end of May the average number of U-boats at sea in the Atlantic had dropped to about 95 and for the first time it was noticeable that U-boats were failing to press home attacks even when favorably situated to do so.

By June 1943, the U-boats were withdrawn from the North Atlantic convoy routes and they succeeded in sinking only 20 ships of 92,000 gross tons during the month. At the same time, 19 U-boats were sunk, by Allied aircraft.

No small part of the success of Allied aircraft against the U-boats was due to the improved microwave radar equipment with which they were fitted. The Allied adoption of microwave radar caught the Germans flat-footed. For some unexplained reason they failed to guess the secret of the improvement which the Allies had made in their radar sets, and in attempting to solve the problem, they ran up against a blank wall. Failing to come up with a technical solution the Germans sought a tactical answer by providing their U-boats with heavier anti-aircraft armament so that they might stay on the surface and fight it out when sighted by Allied aircraft. Though some planes were lost, the principal result of this change in tactics was to provide Allied flyers with more and better targets,

and 4 U-boats that stayed up and fought were sunk in April 1943 and 9 more in May.

Also during the period, sonar gear was so improved that U-boats could not escape out of range by deep submergence and radio sonobuoys were first used during Period V.

During the nine months of Period V, a total of 168 enemy submarines were sunk. Of these, 128 were German, 18 Italian, 18 Japanese, and 4 Vichy French.

The U-boats had made their extreme effort and lost. The world-wide exchange rate as between merchant vessels sunk by U-boats and U-boats sunk fell to three and a half ships to one U-boat, one-third the rate of the previous period. The efficiency of U-boats fell to a new low. The average U-boat sank only about one half a ship of 3,200 gross tons per month at sea, and the average life of a U-boat at sea was reduced to approximately eight and a half months. The expansion of the U-boat fleet was definitely slowed down during the period by the bombing of U-boat bases. The entire increase in German U-boats available was only some fifty.

Total shipping losses of Allied and neutral nations were 491,000 gross tons per month during Period V, or approximately 30 per cent less than during the preceding period. Meanwhile, construction of new shipping, especially by the United States, reached a new high of approximately 1,026,000 gross tons per month resulting in a net monthly gain of about 535,000 gross tons. For the first time during the war, shipping available to the Allies increased, the increase during the period of almost 5,000,000 gross tons bringing the level of total shipping available at the close of Period V to approximately 36,500,000 gross tons. A highly satisfactory increase had also been made in the number of ships available for ocean escorts. The number grew from about 745 at the beginning of Period V to approximately 950 by the end of June 1943. The new ships included some 50 destroyer escorts and 25 escort carriers.

Period VI: Through May 1944.

Period VI of the antisubmarine war, from July 1943 through May 1944, saw the Navies of the United States, Great Britain, and Canada drive the enemy U-boats from the North Atlantic convoy route and into a defensive position in which

their tactics placed first emphasis on self-preservation rather than on aggressive action against Allied shipping. U-boat commanders took to hunting for soft spots.

July saw the invasion of Sicily carried out with no losses from U-boats. During August 1943, 25 U-boats were sunk, 5 being sunk by planes from one American escort carrier the USS CARD. It was estimated that the energetic countermeasures of the Allies were driving the U-boats to their home ports an average of 2 weeks earlier than normal.

The Germans came up with two new weapons. In the Bay of Biscay the Allies had pushed their escort groups as far as possible. This resulted in a violent German reaction through the use of a new jet-propelled radio-controlled glider bomb which sank one British warship and damaged two others. The Germans emerged with a second new weapon in the acoustic homing torpedo, the T-4 and later the T-5, which would track the noise of a ship against which it was fired. How Division 6 of NDRC helped defeat the homing torpedo is described elsewhere in this volume.

Allied countermeasures more than made up for these German innovations.

February 1944 was notable for the 27-day patrol of the Second Escort Group in which every one of six submarines contacted was hunted to destruction. The new sonar apparatus which had been developed was being used with telling effects. The apparatus provided not only the range and direction of an enemy U-boat, but also its depth, and enabled attacking vessels to maintain contact at very close range. The new apparatus made it possible for depth charges to be set for detonation much more accurately than hitherto.

In March 1944 in the Pacific, American antisubmarine vessels scored multiple successes. Perhaps outstanding in achievement was the USS ENGLAND which sank 5 Japanese submarines and took a major part in the sinking of a sixth.

The increased safety of Allied convoys derived in no small part from the painstaking analysis of convoy and antisubmarine operations. In this analysis, the scientists of NDRC both in Division 6 and in the Operations Research Group played an important part. A study of attacks on shipping by U-boats and their results indicated that the safety of independent ships depended very much on the speed of the ship.

On the other hand, in convoyed shipping, speed was the significant factor only in the presence of an air escort.

Another striking result which emerged from the study was that the number of ships sunk in a convoy was on the average independent of the convoy's size so long as the number of escorts was the same. This meant that large convoys would in the long run lose a smaller percentage of ships to U-boat attacks and at the same time there would be a saving in the use of escorts.

The effectiveness of Allied aircraft drove U-boat commanders to adopt a system of complete submergence during the day time, which robbed the submarine of its mobility.

On the part of the Germans, the most revolutionary technical development of Period VI was the fitting of Schnorchel to U-boats. The first U-boats were fitted with Schnorchel in February of 1944.

Improvements to Allied sonar gear came into service use about this time and enabled sound gear operators to determine the bearing and location of targets with much greater accuracy and rapidity. Several improvements in depth charges also came into use on American ships about this time.

All these various advances in equipment, weapons and tactics brought about the sinking or probable sinking of 21 U-boats per month during the eleven months of Period VI. Of the total of 284 U-boats destroyed, 199 were German, 28 were Japanese and 7 were Italian. During the period, the Allied and neutral nations lost an average of 184,000 gross tons of shipping per month from all causes, or about a third as much as during the preceding period. At the same time, the construction of new merchant shipping increased to approximately 1,160,000 tons per month, making a net gain of 976,000 gross tons per month. The total increase of nearly 11,000,000 gross tons made available to the Allies at the end of Period VI, approximately 7,500 ships, totaling 47,500,000 gross tons, of which 10,500,000 gross tons consisted of tankers.

Period VII: Through August 1945.

Period VII, the final phase of the U-boat war, extended from June 1944 to the surrender of Germany on 8 May 1945 and the capitulation of Japan on 14 August 1945.

The final period opened with preparations being made for the invasion of the Continent, 6 June 1944. Every precaution was taken by the Allies against U-boat attacks on the invasion fleet. Ten escort groups effectively walled off the western approaches to the English Channel, and sea and air patrols covered the routes which U-boats might use to approach from Norwegian waters.

During June, 28 U-boats were sunk and U-505 was captured by the escort carrier group which included USS GUADALCANAL, USS CHATELAIN and USS PILLSBURY.

The Schnorcheling tactics of the U-boat were providing effective protection against attacks by Allied aircraft and dependence in discovering U-boats had to be almost exclusively on sonar gear.

The Allied break-through out of the Cherbourg peninsula during the first week in August 1944 forced U-boats to move out of the Bay of Biscay ports and take refuge in Norwegian harbors where the facilities for maintenance and repair were limited and the protection against Allied bombing was far less effective. Late in 1944, the Germans attempted to make use of their fleet of [illegible] submarines, but the effort was far from successful.

January 1945 saw six U-boats sunk, all by surface ships. Allied military operations on land were bringing about further deterioration of the German U-boat position, with the Russian advance in the Baltic area overrunning the facilities for the fabrication and assembly of new U-boats.

German U-boat commanders attempted to defeat Allied sonar gear by spending long periods on the bottom. But sonar operators soon gained experience in countering these new tactics and in February 1945 the sinking of enemy submarines mounted to 19. Of this total, 5 were Japanese submarines in the Pacific, where the American submarine, USS BATFISH, succeeded in sinking three I-class Japanese submarines within four days.

During the early days of May, the U-boat fleet carried on as though oblivious to the approaching disaster to the German land forces. On 5 May 1945 an American [illegible] vessel was sunk off Rhode Island, but the attacking U-boat was destroyed later the same day. On 7 May two ships were sunk by a U-boat off the Firth of Forth. These were the last Allied merchant vessels to be sunk by U-boats during World

War II, as the Japanese between May 8 and August 14 sank no Allied ships while losing six of their own submarines.

The early days of May saw one German submarine sunk in the Bay of Biscay channel area and approximately ten in Danish waters, while an estimated twenty-five U-boats were put out of commission by Allied bombing while in port. On 4 May, Admiral Doenitz told his U-boat crews that the battle was hopeless and instructed them to break off further action. During the remainder of May, forty-nine U-boats surrendered in accordance with Allied instructions and a great many additional U-boats were captured in port or were scuttled. The last U-boat to be accounted for was U-977, which surrendered at Buenos Aires on 17 August 1945 following the Japanese capitulation.

In summing up the U-boat war, it should be remembered that at the close of the war, while the U-boat fleet had been held in check and was definitely on the defensive it was far from being driven from the sea. There is no way of estimating the results which the Germans might have achieved with the new types of U-boats which were just about to begin operation as the war ended.

The closing period of the war was marked on the part of the Allies by the successful development of new tactics and new equipment. More effective search plans were developed, based on analyses by NDRC scientists, which showed that where the correct plan was used contact with a submarine was regained in 44 per cent of the cases, whereas use of an incorrect plan brought a renewal of contact in only 28 per cent of the cases.

The United States Navy, with the assistance of Division 6 of NDRC, continued the improvement of its sonar equipment, looking particularly to developments which would permit contact to be maintained with deeply submerged submarines at short ranges.

The confidence which the Germans placed in the effectiveness of the U-boat despite the heavy losses which they suffered is evidenced by the fact that, though faced with imminent invasion and suffering from a tremendous shortage of manpower, they employed a great proportion of their skilled workers in the improvement of their U-boats and the construction of new designs.

Had the Germans been able to put these new types of U-boats into service use there is a chance that they might have made obsolete all the equipment and devices which Allied scientists had developed.

CHAPTER IX

SONAR GEAR

The wartime need of getting as much equipment as possible into service in the least possible time meant that the scientists and technicians of Division 6 had to turn reluctantly but with determination from the work of fundamental research and of developing new equipment, which they would have liked to have done, to a program of improving equipment already at hand - a program which they ruefully termed "gadgeteering."

As we have seen, many of the anti-submarine vessels of the United States Navy were equipped with good serviceable echo-ranging gear developed by the Naval Research Laboratory and manufactured by the Submarine Signal Company and RCA Manufacturing Company, Inc. The program laid out for NDRC was to devise auxiliary equipment and modifications which could be applied in the shortest possible time to the echo-ranging gear already installed.

Bearing Deviation Indicator

One of the most important improvements to the existing searchlight beam type echo-ranging gear (described in Chapter II) was the Bearing Deviation Indicator. As finally developed, BDI gave to the sonar operator a device which would indicate on the cathode ray tube screen for each echo received whether the target was to the right or to the left of the bearing of the projector. BDI was extremely valuable in helping the operator keep track of a target during the initial rapid turn when the attacking vessel sped toward the contact.

The developmental work on BDI was performed by the Harvard Underwater Sound Laboratory. BDI operated on the principle of lobe comparison, reinvented for this purpose by Dr. C. K. Stedman. Other early experiments were conducted by F. V. Hunt, J. L. Hathaway and X. N. Butz, Jr.

HUSL was not only the developer, but for a time was the producer of BDI equipment for the Navy. In all, HUSL constructed 70 BDI auxiliary units. Later commercially manufactured equipment became available and eventually most of the first-line antisubmarine vessels of the Navy were equipped with BDI.

Maintenance of True Bearing.

Another most important improvement to existing sonar gear resulted from the development of the Maintenance of True Bearing (MTB) system. This device enabled the sonar operator to maintain his projector automatically on any desired bearing with respect to true North, regardless of the movement of his ship. With MTB the operator had only to adjust the training hand wheel to correct for gradual changes in the true bearing of the target, instead of having to keep up with rapid changes in relative bearing as the ship maneuvered.

The work on MTB was carried out at the New London Laboratory.

Receiver Console.

These devices together with a number of other still classified improvements were incorporated in an echo-ranging receiver console. The arrangement of components in the old style sonar rack, with the range and bearing indicator widely separated from the most important operating controls, made it difficult for the sound operator to observe and control the equipment. The new rack, of console type, permitted a concentration of the most important indicators and operating controls in a location convenient for a seated operator and allowed greater accessibility to all the components for maintenance and repair. This new arrangement markedly increased the range and bearing information obtainable per unit of time.

These developments were carried out by the Columbia University Laboratory at New London and by the Harvard Underwater Sound Laboratory. By the end of the war all the principal manufacturers of sonar equipment were in production on console types of echo-ranging gear.

Sonar Testing Equipment.

To design and build improved sonar gear was only part of the task of Division 6. Once the equipment was installed there was the problem of seeing that it worked and that it kept on working at maximum efficiency.

Recognizing the problem, the engineers of the Harvard Underwater Sound Laboratory set to work to design apparatus which could conveniently measure the transmitting and receiving performance of echo-ranging equipment, thus enabling the gear to be tuned and adjusted, tested for operational deterioration and critically compared with other sonar equipment.

Sound Gear Monitor.

A solution to the problem of developing a device which determined receiving and transmitting directivity patterns aboard ship was found in a portable apparatus known as the Sound Gear Monitor (SGM) or in Navy terminology, the Underwater Sound Portable Test Equipment.

With this equipment it was possible to measure the transmitting and receiving frequency response characteristics of sonar gear, the transmitting and receiving directivity characteristics and the approximate transmitted power and receiving sensitivity. In each application the monitor made a direct measurement of the over-all response of the sonar system. Thus the transmitting function of a sonar system was tested by measuring the sound pressure which the projector produced in the water, and the receiving function was tested by evaluating the response of the system to an underwater sound signal of known property.

Tests showed that two portable Sound Gear Monitors were all the equipment necessary to make simple response pattern measurements of sonar projectors. While testing a projector in transmission, one sound gear monitor was used to energize the projector. The second monitor was used as in normal service to receive the sound energy emitted by the projector under test. In testing the receiving function of a projector, the transmitting and receiving roles of the two monitors were interchanged by their respective panel switches.

Once placed in service, the Sound Gear Monitors immediately proved their usefulness. They disclosed a dismaying situation with respect to existing echo-ranging gear on some Navy vessels.

Thus while testing with the monitor on the destroyers USS DAHLGREN and USS YIELDS, the Harvard scientists discovered that apparently because the vessels were fitted with streamlined domes enclosing the projectors, installations

were functioning far below their expected efficiency. Disturbed at this news, the Navy requested HUSL to investigate the problem further on a "local aid" basis.

The findings on DAHLGREN and NIELDS aroused doubt concerning the acoustical performance of dome installations at a time when the Navy had begun to install streamlined domes on all escort vessels so that sonar equipment might be used at higher speeds. A program of measurement was laid out to determine whether the two defective installations were typical.

In all, seventy installations on as many ships were tested. The Harvard scientists were shocked to discover that in many cases the intensity of the sound being transmitted into the water was so low as to render the echo-ranging equipment virtually useless. Equipment with unpainted domes was found to have considerably better patterns than those with painted domes. Yet even the patterns of gear with unpainted domes were still inferior to those of equipment at test stations. It became apparent that the anti-fouling painting, while an important factor, was not the only cause to which the deterioration of projector patterns could be attributed.

Tracking down the source of this poor performance, the Harvard research workers made a discovery in tests on the destroyers USS KENDRICK, USS LAUB and USS MACKENZIE, all of which had been equipped with unpainted domes. When tests made with the Sound Gear Monitor showed that these domes were seriously impairing the performance of the sonar gear, the domes were replaced by new corrugated models which had been found to be superior to the older domes. But the measurements taken after the installation of the corrugated domes revealed that the sonar equipment had suddenly become almost, wholly inoperative. Despite the fact that the electrical performance was excellent, acoustically both the transmitting and receiving responses were found to be at least 20 decibels or ten-fold below reasonable expectations.

This was bad news to those responsible for the imminent sailing of these vessels for convoy escort duty. During the heightened activity which followed the discovery, study of the evidence suggested that some feature of the commercial anti-freeze solution used to fill the dome was the cause of the failure. A laboratory experiment was quickly arranged which showed that when the transducer was dipped in the anti-freeze solution it collected a thin wax-like deposit which caused a sharp drop in its response. On the basis of this

crude experiment the USS Kendrick was placed in drydock so that the interior of the dome could be inspected. The expected layer of wax-like substance was found covering the projector surfaces and the interior of the dome. The deposit was removed, the dome was replaced and filled with salt water. The results were excellent. The patterns approximated those obtained at test stations. Similar treatment of the domes on the USS LAUB and the USS MACKENZIE were equally effective. A simple change in procedure of filling the domes was suggested which eliminated the formation of wax deposits. This meant the difference between submarine defense and vulnerability for at least one convoy.

As eventually developed, two portable types of Sound Gear Monitor known as Model OAX and Model OCP went into commercial production and several thousand units were delivered for Fleet use. Development work on a permanently installed type called the Installed Sound Gear Monitor (ISGM) was carried on, but not to the point of procurement of commercially manufactured units.

Dynamic Monitor.

Helpful though it was in indicating whether the essential functions of sonar gear were operative the Sound Gear Monitor did not have enough panel adjustments to be used easily for quantitative measurements on the over-all performance of the sonar equipment under conditions of normal echo-ranging. Thus the engineers of the Harvard Underwater Sound Laboratory turned to the development of the Dynamic Monitor, a device designed to provide a numerical index, called the "figure of merit," of the over-all acoustical performance of sonar echo-ranging equipment. Measurements of the "figure of merit" - defined as the ratio in decibels between the transmitted intensity of a ping at a distance of one meter from the projector face, and the minimum sound intensity which will constitute a detectable echo under the prevailing conditions of ambient noise - permitted valid objective comparisons to be made between different types or conditions of sonar equipment, not only when the installations were on the same ship, but also when they were on different ships.

For comparison purposes, the Dynamic Monitor utilized a cathode ray tube. This gave a direct reading of the figure of merit after two preliminary calibration adjustments. The procedure was a substitution method by which the measured figure of merit was independent of the calibration of the electronic

equipment of the Dynamic Monitor and of the monitor transducer. Only one model of the Dynamic Monitor was constructed and no effort was spent in refining the design so that the apparatus could serve as a production prototype.

Submarine Noise Reduction.

The submarine noise reduction program required sound measurement apparatus in order to determine standards of acceptably quiet performance which would be calibrated in absolute terms and so permit comparison among the results obtained at different bases and on tests with different ships. The New London engineers undertook to assist in the development of a device to meet this problem. The result was the design of Model OAY Sound Measuring equipment which provided readings of sound pressure level over a frequency range from 100 to 20,000 cycles per second directly referred to 0.0002 dyne per square centimeter and over a dynamic range of 110 decibels. The gear was most useful for overside measurements of submarine sounds, particularly for detecting abnormally noisy auxiliary machinery units during the course of construction. The equipment was made up as a rugged portable unit and was sufficiently flexible in its applications to permit various types of sound measurements on shore, on shipboard, or from small boats.

Not only could noisy auxiliary machinery units be detected and the trouble remedied before the ship left the yard, but overside measurements could also be made on submarines in commission or when they were at dock, secured to buoys, or anchored or drifting. The OAY equipment was customarily located aboard the surfaced submarine with the hydrophone hung overside at a standardized location as near as possible to the noisy part of the auxiliary machinery to be measured. Noise level readings thus obtained in absolute units could be compared with the standard values for acceptable performance, as previously determined. The OAY had a response that was flat for 100 to 10,000 cycles per second and was good to 20,000 cycles per second.

Many OAY units were put into use at submarine bases throughout the world and the equipment found application in other types of sound tests where a rugged portable instrument with a wide flat frequency response was needed.

CHAPTER X

AIRCRAFT DEVICES

Admiral Doenitz had boasted that his submarines were as immune from detection and attack by Allied planes as a mole is safe from a marauding crow. There was a good deal of truth in the Admiral's boast; but American scientists had an answer. With airborne radar and with the Airborne Magnetic Detector (MAD) and the sonobuoys which Division 6 developed, and the improved ordnance which Division 6 helped to devise, they gave Allied planes an effective means of detecting and attacking the Nazis' U-boats.

Magnetic Airborne Detector

Even before the formation of Division 6, Dr. L. B. Slichter had been interested in the detection of submarines by magnetic methods. In April and May of 1941, Dr. Slichter, in company with Dr. Tate, visited the United Kingdom and there devoted considerable study to the work being done by the British on the detection of submarines by magnetic means. Upon his return to the United States, Dr. Slichter organized a group under the newly-established Section C-4 to undertake a preliminary investigation of magnetic detection at Massachusetts Institute of Technology. This was the group which later was transferred to the Naval Air Station at Quonset Point, Rhode Island.

With the entry of the United States into the war, the program of the group was expanded and in March of 1942 the center of activities was moved to LaGuardia Field, New York. Operational bases were maintained at the Lakehurst, New Jersey, Naval Air Station and at Langley Field, Virginia. In September 1942, with the work still expanding, the group was moved to Mineola, Long Island, into a hastily constructed laboratory which became known as the Airborne Instruments Laboratory. Still later a West Coast laboratory was established at the Harlow Aircraft Company at Alhambra, California. For their experimental work with MAD the scientists had the use of a bi-motored Grumman JRS-5 plane.

The original group working on the MAD project consisted of Dr. Slichter, Dr. J. N. Adkins, Dr. N. A. Haskell, Mr.

Judson Mead and Mr. C. S. Pearsall. In August 1941 the group was joined by Dr. D. G. C. Hare, who later became laboratory director, with Mr. W. B. Lodge as assistant director.

The detector element used in MAD had previously been incorporated in a magnetic mine device developed, under a contract with NDRC's Section D-3, by Mr. V. V. Vacquier of the Gulf Research and Development Company under the direction of Dr. E. A. Eckhardt. The latter had brought the detector element to the attention of Division 6 and ultimately another contract between NDRC and the Gulf Laboratory was drawn up. This contract was later supplemented by contracts with the Western Electric Company and the General Electric Company for work on various types of magnetic detectors. As the work grew, so the staff grew, and by the end of 1942 a total of 160 people were working on the project and by the end of 1943 more than 350.

The operation of MAD depends upon measuring the distortion in the magnetic field of the earth caused by the presence of the ferro-magnetic mass of a submarine. The magnetic field of the earth has a total intensity of about 60,000 gammas, one gamma being equal to 10^{-5} gauss. The distortion of this field due to the presence of a submarine at a distance of a few hundred feet is of the order of only a few gammas.

A major problem faced by the researchers resulted from the fact that the earth's magnetic field is a vector quantity. Thus relative motion between it and the sensitive axis of the measuring device will produce indications of changes in field intensity. These spurious indications must either be neutralized or the effects of the relative motion between the measuring device and the earth's magnetic field must be eliminated. False signals may also be created by the magnetic field produced by the aircraft itself.

How successfully this major problem was solved is indicated by the fact that the MAD equipment, as finally developed, had a background noise level of only some 0.2 gamma under conditions of reasonably straight and level flight and of not more than a few gammas under conditions of rapid maneuvering. Thus the equipment was capable, in even flight, of detecting a submarine where the magnetic anomaly produced by its presence was only a few gammas.

An experimental device constructed by the Sperry Gyroscope Company according to the Gulf Company's specifications

was made available for tests. This instrument employed the saturated core magnetometer developed by Vacquier. Modifications and improvement of this instrument resulted in the development of MAD Mark I.

Although usable signals could be obtained from S-type submarines, the operation of MAD Mark I was not entirely satisfactory. The chief trouble lay in the fact that since the detecting coil was stabilized by means of a gyroscope, the fluctuations caused when the plane banked in going around a curve were such as to obscure almost completely the minute changes in magnetic intensity. It was realized that a far more satisfactory method of orienting the coil would be to use the earth's magnetic field itself.

Despite its deficiencies, the Mark I MAD was installed in Navy blimp K-3 and saw service use. Meanwhile, of course, the development work continued and MAD Mark II was produced by the Gulf Company. A total of 14 Mark II units was produced and placed in service.

Experimentation looking to the development of methods for using the magnetic field alone to control the stabilization of the magnetometer were undertaken by several of Division 6's contractors. The Bell Telephone Laboratories succeeded in producing a magnetically oriented instrument using saturated core magnetometers of the second harmonic type.

Meanwhile, the Airborne Instruments Laboratory of Division 6, operating under a Columbia University contract, was not only conducting experimental work of its own but also did the testing for other groups engaged on the problem of magnetic detection. Laboratory staff members accumulated a total of more than 9800 flight hours. They were present during numerous bombing attacks on submerged targets, witnessed several torpedoings and rescues, and acted as technicians on the blimps and planes in which MAD apparatus was installed.

The ultimate result of this work was the development of the MAD Mark IV, Mark IV B-1 and Mark IV B-2 systems and the eventual production model AN/ASQ-1, and an experimental model, AN/ASQ-2. Development of the BTL instrument, later known as the Mark X, was continued under NDRC direction to the stage of field tests upon a working model. After further development under direction of the Naval Ordnance Laboratory, approximately 50 Mark X units were produced by the Western Electric Company under a Navy contract.

These instruments were all based on the magnetic stabilization of the magnetometer head without the use of any gyroscope. MAD produced a continuous trace on a moving tape and distortion of the trace indicated passage near a magnetic body, such as a submarine.

The principal value of the equipment lay in patrol work over restricted waters such as the Straits of Gibralter, where the MAD-fitted planes of Navy Squadron VP-63 and the blimps of ZP-14 did notable work in aiding to maintain a barrier against the transit of German U-boats to and from the Mediterranean.

It was on 24 February 1944 that Planes 14 and 15 of VP-63 made the first successful MAD contact with a U-boat in the Straits. With MAD, they tracked and bombed it, and with the aid of British destroyers and planes scored a certain kill. On 16 March and 15 May, two almost sure sinkings of U-boats were marked up as the result of MAD detection.

Planes equipped with MAD were given a suitable weapon through the work of another NDRC Division - Division 8, which developed the retro-firing rocket bomb and its companion, the retro-firing flare. Since MAD detected a submerged submarine when almost directly over the target, it was desirable to have a projectile which would drop vertically. This was accomplished in the retro-firing bomb, which was projected backward at a speed equal to the forward speed of the plane. The two speeds offset one another and the bomb plummeted downward in an approximately straight line.

Despite the value of MAD in its specialized field, there was still need for further devices if the airplane was to be a successful hunter of submarines. And once again the resort was to underwater sound.

Expendable Radio Sonobuoy.

Out of the work of the New London Laboratory of Division 6 on aircraft listening systems came the Expendable Radio Sonobuoy (ERSB). The principle of the ERSB had been proposed earlier for a device used for the protection of convoys. A buoy could be dropped overboard from a convoy ship and as the convoy proceeded on its course the buoy would pick up the waterborne sound of any vessel approaching from astern and transmit a warning by radio to the convoy. Instead of being dropped from a ship, the Expendable Radio Sonobuoy was designed

to be dropped from a search plane when it knew or suspected that a submerged submarine was in the area.

ERSB consisted of an underwater listening device which picked up the sounds of a submarine and transmitted them to a radio set which then sent the sound to the listening airplane. The buoy's radio range was dependent on the altitude of the plane. Frequency-modulated radio transmission was used in view of the stringent noise suppression requirements and to obtain freedom from interference. Buoys could be operated on any of six radio frequencies. Multi-channel reception in the receiver made it possible, by operating a selector switch, to listen to any desired buoy.

The radio sonobuoy met an urgent need. With disheartening frequency planes and blimps sighted enemy submarines only to see them maddeningly crash-dive to safety before a successful attack could be launched. By the time surface ships arrived--usually a matter of hours or even days--it was, more often than not, too late to regain contact by echo-ranging. The Navy's antisubmarine experts outlined the problem to the underwater sound group at Columbia University's laboratory at New London, where W. B. Snow, assisted by J. W. Horton, was placed in charge of the new project. Later, A. G. Wamback was made supervisor, with J. A. Barkson as his principal assistant.

The first tests were designed to show whether or not the fundamental idea was practicable. Two convoy type buoys were used and were placed in the water by a launch. Then with a submarine serving as a submerged target, listening tests were conducted aboard the blimp K-5 by means of a radio receiver installed for the purpose. As the blimp circled overhead the submarine's propeller sounds were clear and distinct in the headphones. Radio reception continued good as the range was increased. Then the submarine also moved away from the buoy; and still its noise could be heard and identified by listeners aboard the blimp. Obviously, the basic idea was sound.

Encouraged by these results the research team went to work. J. T. McNary and W. L. Widlar rushed the Mark I transmitter model to completion - producing what amounted to an entire frequency modulation broadcasting station on a round chassis less than five inches in diameter and under ten inches long. R. A. Fox, basing his work on the electrical features of the convoy unit, was striving to complete a

receiver with drastically reduced size and weight suitable for aircraft use. A. L. Thuras, starting from scratch, came up with a magnetostriction hydrophone, the response characteristics and the ruggedness of which were ideally suited to meet the sonobuoy requirements. Meanwhile, R. I. Mason was working on the difficult launching problem.

Beginning with the Mark II Model, various schemes were tried for getting the buoy safely into the water. After various attempts a Mark III unit was eventually fitted with a small parachute and dropped 500 feet. The parachute solved the problem. The buoy worked perfectly with no carrier frequency shifts or other damage of any sort.

With the completion of the Mark IV-B unit, Navy and Army experts were agreed that the buoy was ready for operational tests. Pre-production quantities were ordered and a month later, only five months after the start of the development work, some of the units had already been used in actual offshore operations against the enemy.

The Mark IV-C and Mark IV-D buoys incorporated additional improvements and final redesign was accomplished in order to incorporate revisions making the unit easier to produce in quantity. Production models were known as AN/CRT-1 and AN/CRT-1A

The sonobuoys gave the pilots of antisubmarine patrol planes what they needed - the ability to hear a submarine under water. In service, they used the buoys singly in order to check suspicious signs such as oil slicks, disappearing radar blips or MAD indications. For tracking, a number of buoys were dropped in a definite pattern and the path of the submarine was traced by means of the changes in the relative intensity of the sound from the different locations.

CHAPTER XI

ANTISUBMARINE ORDNANCE

The story of Division 6's achievements in the field of antisubmarine and pro-submarine ordnance must of necessity be far less than half-told because of omissions required for continuing security reasons.

As has been mentioned in the introductory chapter, one of the major projects of Division 6 had to do with the development of improved torpedoes. Extensive research on the principles of underwater travel, flight in air, and water entry, produced an aircraft torpedo which could be dropped from great heights and from planes flying at high speed. There need be no more low-speed minimum altitude attacks such as proved so costly at the Battle of Midway.

The concern of Division 6 with the development of various types of projectiles dated back to 1941. The need for knowledge concerning specific projectile characteristics first arose in connection with the attempt of Division 6 to develop more effective antisubmarine weapons. As the needs of the Division grew, so too grew the list of projectiles until it included rockets of many types, bombs, shells, and torpedoes. In addition to the characteristics specifically required of each projectile, all of the projectiles were expected to have consistently accurate travel to the target and to utilize efficiently the applied propulsive force. The methods of propulsion investigated varied over a wide range, from simple fall under the action of gravity to continuous propulsion by means of propellers or jets.

Research on Fluid Dynamics.

Early in the life of Division 6, a brief investigation showed that comparatively few reliable data were available concerning the fluid dynamic forces acting on a projectile of a given shape. It was evident that if reliable information to guide the design engineer was to be realized there must be a program of laboratory research. Thus, the Division 6 research program on fluid dynamics was born.

It should be noted here parenthetically that the term "fluid dynamics" is used rather than aerodynamics, or hydrodynamics. The reason for this is that in the list of projectiles with which Division 6 was concerned were many which had the first part of their travel path in air and the second part in water. To insure acceptable performance such projectiles had to travel accurately through each of these very dissimilar media.

Moreover, it was soon found that to regard the travel of the projectile having a combined air-water path as being simply divided between a period of air travel and a period of water travel unduly simplified the problem. Very frequently in such cases, the transition period of water entry proved to be of major importance. During this moment there are very obvious possibilities of mechanical damage to the projectile. Also, completely apart from the damage that might be produced, the fluid forces applied to the projectile during the entry period might also cause it to emerge from the water, or change direction sharply, or get out of control and assume an erratic path in its subsequent underwater travel. As these facts were realized, they clearly demonstrated the need for special studies of the dynamics of water entry.

The first studies of projectile dynamics undertaken by Division 6 were carried on by the New London Laboratory. These experiments were designed to improve the sinking rate and accuracy of path of depth charges. Nearly five hundred tests were made in a 100-foot training tank.

Later, some 700 experiments, also with scale models, were conducted at the swimming pool of Massachusetts Institute of Technology. The tests were aimed particularly at gaining knowledge concerning the phenomena of water entry. The models were projected from an air gun and high-speed moving pictures recorded the underwater travel.

California Institute of Technology Contracts.

The results of these early experiments pointed to the need of a more extensive research program. Consequently, a contract (CEMsr-207) was entered into with California Institute of Technology to provide for the use of the facilities of the Institute's Hydrodynamics Laboratory.

The first research equipment constructed under this contract was the high-speed water tunnel. The polarized light

flume, a small piece of equipment used for the visual study of the flow patterns around projectiles, was developed at the same time as an accessory to the main tunnel. At a considerably later date the design and construction of a controlled atmosphere launching tank and of a free-surface water tunnel were undertaken. Each of these pieces of equipment is described in subsequent sections of this chapter.

This project was carried out under the direction of Dr. R. T. Knapp, Dr. Vito A. Vanoni, in his capacity of associate director, shared the load of both technical and administrative responsibility. Dr. James W. Daily, as assistant director, aided in the general operation of the project and in particular in the preparation of the reports. Joseph Levy, H. L. Doolittle, R. M. Peabody, and G. E. Robison, were project managers who supervised the individual tests and evaluated the results presented in detailed reports. H. B. Boller and R. L. Page were responsible for a large part of the mechanical design of the new instruments and equipment which were made necessary by the demands of the work. Haskell Shapiro and Clarence M. Edwards played a similar part in the development of the rather complicated electrical and electronic devices that were required. Garrett B. Van Pelt and Mrs. Elizabeth Thorne were responsible for the long series of flow studied made in the polarized light flume. Robert Carr and Lee Holland were in charge of the actual operation of the high-speed water tunnel and the makings of all the test measurements. Hugh Stevens Bell and Miss Althea Pease carried the responsibility of meeting the laboratory's photographic needs, not only for the normal demands, but for the development of carrying out the many specialized techniques involved in using photography as a measuring tool. W. W. Baustian, H. Thorne, and Rudolph Lorman were in charge of the construction and maintenance of the instruments and equipment and the production of precision models that were required for the work. There were numerous others who aided in the project.

Shortly after the work on the high-speed water tunnel had been started, a separate contract (OEMsr-329) was arranged with California Institute of Technology for "studies and experimental investigations in connection with the descent of underwater projectiles when falling freely and when initially propelled." Under Dr. Max Mason as official investigator, a laboratory was set up at Morris Dam, east of Pasedena. The group there was concerned chiefly with tests of underwater ordnance being developed or improved for service use, as described later in this chapter.

High-Speed Water Tunnel.

There were several reasons for the choice of water as the fluid medium for the experimental measurements of the dynamic forces on projectiles. In the first place, at the time of the initiation of the work, the projectiles under consideration were principally those having only underwater paths. In the second place, it was known that the phenomenon of cavitation was involved frequently in the underwater behavior of projectiles. Since cavitation is a phenomenon that is peculiar to motion in a liquid, there was no satisfactory way of studying it in anything other than a water tunnel. In the third place, the equipment available as a nucleus for the work was adaptable to use with water and not with air.

Finally, it can be shown that over a wide range of conditions the results obtained by a study of projectiles in a water tunnel are applicable to the projectile whether in air travel or in water travel. The only serious limitation is that when the results are applied to air travel they must be restricted to cases in which the projectile velocities are sufficiently low so that the air can be treated as an incompressible fluid. This means in general that the results obtained in the water tunnel can be applied with acceptable accuracy to the air flight of projectiles having velocities of less than 700 feet per second.

The high-speed water tunnel was a vertical, closed-circuit tunnel in which water was circulated continuously by means of a propeller pump driven by a variable speed motor. The working section, which was 14 inches in diameter and six feet long, was located in the upper horizontal run of the circuit. It had the smallest cross-section and consequently the highest velocity and the lowest pressure in the circuit. The velocity in this section could be maintained at any desired value up to 70 feet per second. The models of the projectiles or other devices to be tested were mounted on the spindle of a three-component balance of the National Physical Laboratory type.

Measurements of the drag force, the cross force, and the moment could be made with a projectile aligned parallel to the direction of flow or rotated in the horizontal plane to any desired yaw angle between ±20 degrees of the direction of the flow. The absolute pressure in the working section was controllable independent of the velocity and could be held at any desired value from five atmospheres down to the vapor pressure of the water. The working section was provided with

large lucite windows for visual and photographic observation. Cameras with synchronized flash lamps of the Edgerton high-speed type were a regular part of the equipment.

Although the propeller pump and drive motor produced considerable noise in the audible range, it was found that the tunnel was comparatively quiet in the sound range above 6,000 cycles per second. Therefore, microphones mounted at the focal points of spherical and ellipsoidal reflectors were developed for investigating the sound produced by the flow passing the projectiles both under cavitation and non-cavitating conditions. These reflectors had double walls enclosing an air space and were installed in a water-filled tank attached to one of the lucite windows directly opposite the model under test. Sound measurements with this equipment were made in the range of from 10,000 to 100,000 cycles per second.

In order to study the effect of the propeller drive on projectiles, small electric motors were developed that could be mounted within the models. These motors proved to be capable of driving the propellers at correct model speeds and thrusts. The actual operating speeds of the propellers were as high as 18,000 rpm.

Polarized Light Flume.

The polarized light flume developed to make possible the visual studies of the flow patterns around various types of projectiles was similar to the high-speed water tunnel in principle but was on a much smaller scale. It had a working section six inches wide, 12 inches deep and four feet long, and operated only at low velocities, the maximum being in the neighborhood of five or six feet per second. A suspension of a minute quantity of very fine clay particles in the water of the flume made the flow pattern visible when the water was veined with transmitted polarized light. Although the results from this flume were purely qualitative they proved to be very useful not only in delineating the general flow pattern, but also in locating various sources of disturbance which might result in an increase in resistance or a loss in stability.

Controlled Atmosphere Launching Tank.

The controlled atmosphere launching tank with its associated apparatus was constructed for the purpose of studying

the problem of water entry. As the name implies, the apparatus differed from the majority of the existing launching tanks in that provision was made to control the atmospheric pressure above the water surface. This control was necessary when working with scale models of projectiles, because simulation of the conditions that exist when full-size projectiles are launched from air into the ocean, requires that the air pressure be reduced in the same ratio as the linear scale of the model projectile. The controlled atmosphere launching tank was a late development and was completed only a short time before research under OSRD terminated.

Free-Surface Water Tunnel.

During the course of the research work numerous problems arose in connection with the underwater travel of projectiles which could not be investigated satisfactorily using the high-speed water tunnel or other equipment available in the laboratory. One of the problems concerned the study of the behavior of projectiles, such as torpedoes, when they are traveling so close to the surface that the flow of the surrounding water loses its symmetry. Another such problem involved the effects of underwater jet propulsion, a study of which necessitated the introduction of comparatively large quantities of gas into the flowing water in the test section.

A free-surface water tunnel was designed in order to make it possible to study these and similar important problems. In principle it was quite similar to the high-speed water tunnel but it had a larger working cross-section, 20 inches square as compared to the 14-inch diameter of the high-speed water tunnel. The upper surface of the stream was in contact with the air, the pressure of which could be controlled.

Cavitation Studies.

More effort was devoted to studies of the various aspects of the cavitation phenomenon than to any other phase of the Hydrodynamics Laboratory's work. The reason for this was that basically the effects of cavitation constitute one of the most serious limitations to the satisfactory performance of underwater projectiles. Furthermore, less was known about cavitation than about most other hydrodynamic phenomena.

The first general study in this field made by the Laboratory concerned the production of supersonic noise by cavitation,

and the movement of the sound source and the variations in intensity that accompanied the development of cavitation from the incipient stages to a bubble that enveloped the entire projectile. Later, an extensive study was made on the effect of nose shape on resistance to the development of cavitation with special emphasis on families of ogives, spherogives, and ellipsoids. Studies were also made to determine the effect of various degrees of cavitation on the drag resistance and the control and stability characteristics of projectile shapes.

Although the many different torpedo shapes studied had widely differing dimensions, they had many characteristics in common. Therefore, an attempt was made to integrate these results in a general analysis of the effect of body shape and the size, shape, and location of control surfaces on damping and dynamic stability of torpedoes.

At the war's end, none of the studies made by the Hydrodynamics Laboratory could be considered as complete. In fact, the research workers felt that they had only gotten started. While the research program was directed wholly toward the war effort, it resulted in the development of equipment and techniques of measurement which could be most usefully employed in further research, not only in military, but in civilian fields. A good example of this was evident in the field of cavitation research. Here practically all of the results are equally applicable to the movement of underwater bodies such as projectiles and submarines, the operation of ship and torpedo propellers, and the behavior of general hydraulic machinery, such as centrifugal pumps and turbines for hydroelectric development.

Studies at the Morris Dam Laboratory.

In carrying out work on the underwater properties of projectiles there are two main problems in devising laboratory equipment: providing devices for dropping or launching the projectiles, and developing recording apparatus which would supply accurate information on underwater behavior.

A drop platform, a launching trolley, a pendulum launcher, and rocket propulsion were variously used at the Morris Dam Laboratory. The various launching devices could give, besides vertical drop, a variety of speeds and angles of entry. For recording purposes, hydrophones and cameras were principally

used. Motion picture cameras could catch the behavior at water impact and underwater cameras the subsequent behavior. Thus it was possible to get accurate information on underwater trajectory and speed of descent.

For fuze studies the fuze mechanism could be modified so that a click, which would be picked up by the hydrophones, would indicate the depth at which arming had taken place. Fuze functioning on impact could be studied by submerging a target and modifying the fuze so that a click was substituted for normal detonation. In this way it was possible to tell at what angles of impact and against what substances -- for instance, the steel plate or wooden deck grating of a submarine -- satisfactory fuze functioning could be expected.

In order to carry on fundamental studies, a second laboratory was set up to study entry and underwater-trajectory behavior of small-scale models. The equipment of this laboratory consisted of a glass-sided tank and a launching device operated on the cross-bow principle. The latter could be adjusted to give a variety of entry angles and entry speeds. High-speed cameras, including a rotating disc camera, set facing the glass side of the tank and synchronized with the trigger of the launching mechanism, recorded the entry and subsequent trajectory of the model.

In this way, a considerable amount of information was accumulated concerning the behavior of models with a variety of head or nose shapes. As any projectile -- model or full scale -- enters the water, it carries with it air which forms a bubble. The shape of the entering portion of the projectile determines the size and shape of the bubble. As the projectile goes through the water, the bubble attenuates and finally collapses, the trajectory being determined to a considerable extent by the shape of the bubble and the position of the projectile in relation to it. The photographs made of launchings in the model tank gave a very detailed record of bubble phenomena.

When the torpedo-launching station (described in the next section) was working with full-size aerial torpedoes, accurately built scale-models, one inch in diameter, were tested in the model tank. Comparisons of full-scale and model launchings showed that small-scale tests could not be extrapolated to prototype size without danger of erroneous conclusions on entry phenomena. Modification of the models resulted in behavior more consistent with the performance of

the full-size torpedoes. The next step was to work out fundamental theory which would bring the basic concepts of small-scale modeling into a more serviceable relationship with full-scale performance. This investigation was in progress when the war ended. It forms part of the continuing program of research which, along with the Morris Dam Laboratory and the model tank, is being carried on by the underwater ordnance section of the Naval Ordnance Test Station, Inyokern, California.

Torpedo Launching Station.

In the fall of 1942 the Bureau of Ordnance requested NDRC to undertake the development of a new aircraft torpedo which would give satisfactory performance when dropped from high-speed planes at higher altitudes. Such a development was a major enterprise. Within NDRC, Division 6 was given responsibility for the design work and Division 3 for furnishing basic information for the design. The Morris Dam Laboratory set up a torpedo launching station, where California Institute of Technology groups under contracts with both Divisions worked together under the supervision of F. C. Lindvall. The Division 3 part of the work (under contract OEMsr-418) involved full-scale studies of the fundamental hydromechanical phenomena associated with high speed water entry of torpedoes.

The general problems which were set for the CIT torpedo launching range were:

(1) General hydrodynamic effects at entry.
(2) The effect of dynamic characteristics of the torpedo.
(3) The effect of nose and tail structures on entry and underwater trajectories.
(4) The determination of underwater trajectories.
(5) The measurement of deceleration forces and the effects on structure and mechanisms of the consequent impact loadings.
(6) The general structural aspects of the entry problem.

In particular, dynamic loading data were sought which could serve as a basis for future torpedo design. Furthermore, as a general problem, the Mark 13 torpedo was to be studied under controlled entry conditions for clues to improvements in both dynamic and structural behavior.

Functionally the work divided itself into engineering design and structural analysis of torpedo bodies and components,

torpedo-borne instrument development, external photographic equipment, external instrumentation, underwater trajectory determination, torpedo control studies and operation of the launching facilities.

Various general schemes for accelerating and launching the torpedo were studied leading to a final decision for the construction of a 300-foot tube for compressed air launching. After a number of improvements in design and construction, the launching tube met general design specifications for entry angle and velocity and put the torpedo into the water with very small amounts of random pitch and yaw.

For determination of underwater trajectories an acoustic range was designed and installed, utilizing an array of twelve hydrophones with suitable amplifiers and a recording oscillograph. Various noise sources within the torpedo were tried, leading finally to a timing device installed in a torpedo hand hold which fired detonating caps at suitable intervals. Eventually a mechanical computing device was developed for reduction of oscillograph data to actual trajectories.

In addition to standard motion picture cameras for recording the actual water entry from the rear and the side, a rotating disc camera was developed which gave on a single photographic plate the position of the torpedo at each thousandth of a second during entry. Special flares were produced for mounting on the torpedo to give sharply defined slit images on a photographic plate which could be accurately measured on a comparator. From these position-time records the velocity and deceleration during entry could be determined with a high degree of accuracy.

Dummy torpedoes were designed and built to serve as flying laboratories to carry deceleration measuring instruments, structural elements and portions of actual torpedo mechanism. These dummies were built to receive various types of head and tail structures for entry behavior studies, and to permit changes in the dynamic constants of the torpedo.

Depth Charges and Bombs.

Work was also done on the development of fuzes for fast sinking depth charges. Two special types of firing mechanisms were developed.

Depth charges, like aircraft torpedoes, have both air and water flights. Several different designs of depth charge were studied chiefly to determine their drag and stability with a view to improving their accuracy and increasing the velocity of their fall in the water. Similar studies were also made on a group of aircraft bombs.

Still another development in the field of ordnance was the depth charge intervalometer. The use of closely spaced patterns of fast sinking depth charges from surface craft imposes demands on the release gear not likely to be fulfilled by manual operation. As finally developed, the depth charge intervalometer had as its heart a 25-position 6-bank rotary selector switch which connected the electrical firing circuits to the various tracks and projectors at the correct time and in proper sequence.

Also developed was the Mark 53 bomb rack which made it possible to launch fast sinking depth charges from lighter-than-air craft as well as from surface crafts.

Lastly, there was the antisubmarine scatter bomb. This was a cluster of small shaped-charge projectiles with an appropriate scattering and fuzing mechanism. The weapon could be launched from standard airplane bomb racks, and was designed in such a way that after release the projectiles spread out to form a regular pattern when they struck the water. They armed in the air after a short delay and fired on impact with a surfaced or submerged submarine.

Lights and Flares.

Float lights and flares were also developed by Division 6 and, though not strictly ordnance items, they may be discussed briefly here.

The Mark V and Mark VI float lights were developed at the New London Laboratory for use by sonobuoy-equipped aircraft, to replace the Mark IV which had too short a burning time for a blimp, after it had dropped a flare to mark the location of a suspected target, to circle and return to the target area. The Mark VI was essentially a group of Mark V's mounted in a single unit and so arranged as to burn in series. Its primary use was to mark the position of aircraft-launched ERSB's.

The development of underwater flares as an aid in the detection of submarines at night was undertaken at a time when U-boats were operating in the comparatively shallow waters off the Atlantic Coast of the United States. Later, when the U-boats had been forced to retire to deeper waters where flares would have been useless, the project was dropped, but not before a tragic accident had occurred on the night of 8 June 1942. Two Navy blimps participating in tests of underwater flares collided. With the exception of one Naval officer, all aboard were killed, including five NDRC scientists: Franklin C. Gilbert of the New London Laboratory; Israel H. Tilles and Arthur B. Wyse of the San Diego Laboratory; Laurence S. Moyer, special adviser to Division 6; and Charles R. Hoover of Division B, which was cooperating in the underwater flare research.

Research on Rockets.

In addition to its work for Division 6, the Hydrodynamics Laboratory at California Institute of Technology also aided Division 3, which was responsible for the development of rockets. The Laboratory carried out an extensive program of tests on rocket characteristics. Many of the troubles encountered in rocket behavior developed during the burning of the propellant charge. It was found that water tunnel measurements of the forces acting on the rocket body could be correlated with the behavior of the rocket during this initial period and could be used to develop shapes that would have the desired performance characteristics. The rockets for which model studies were made ranged in size from the infantryman's bazooka to the Tiny Tim aircraft rocket with its diameter of nearly 12 inches.

Some cavitation studies were also made in conjunction with these rockets since some of them were designed for use against underwater targets. Most of the rockets studied were of the fin-stabilized type, but it was also found that the water tunnel measurements were of use in the design of spin-stabilized rockets. The properties of several of the latter type of projectiles were investigated in the tunnel.

CHAPTER XII

MISCELLANEOUS DEVICES

Harbor Protection.

Among the harbor protective devices were the Cable-Connected Hydrophone system and the Anchored Radio Sonobuoy.

The Cable-Connected Hydrophone System consisted of a series of regularly spaced tripod-mounted hydrophones connected by submarine cable to a shore station where a switching mechanism and a sonic listening amplifier were provided. The system enabled the forces guarding a harbor to detect and determine the approximate location of an enemy submarine which might approach the harbor entrance.

The NDRC developmental work on the Cable-Connected Hydrophone System was done by the New London Laboratory in close cooperation with the Naval Research Laboratory. An initial system was installed near the entrance to Block Island Sound and later, on the basis of experience with this system, a second system was installed at Cape Henry, Virginia.

Division 6 also contributed materially to the development of the Anchored Radio Sonobuoy. This device worked according to the principle already discussed in connection with the Expendable Radio Sonobuoy. When located in a harbor, the anchored buoy picked up underwater sounds and transmitted them by radio to a shore receiving station. Known as the JM buoy, the original model was developed by the Naval Research Laboratory for the Navy's Bureau of Ships. Division 6 aided in the selection of the hydrophone, made various suggestions for improvements of the early production models, and helped in personnel training and in the development of methods of anchoring and managing the cables to eliminate noise and tangling. The ARSB was reserved for use in deep water and for auxiliary or emergency use at advanced bases where the expenditure of time, material, and effort needed for a Cable-Connected Hydrophone system was not justified.

Attack Aids.

Various types of attack plotters were worked on by the General Electric Company, Armour Institute and HUSL. The Antisubmarine Attack Plotter developed by the General Electric research workers was adopted and widely used. This was an electronic device by which the relative positions of own ship and target were shown on a cathode ray Plan Position Indicator and firing time was indicated by a system of lights.

Sonic Listening Gear.

It had been recognized shortly after the outbreak of the Pacific war that there was need for sonic listening equipment capable of detecting sounds produced by stationary or slowly moving surface craft and of indicating at the same time any detectable noises produced by the submarine itself. At that time the standard listening equipment on U. S. Navy submarines was designed for the reception of sound in the supersonic frequency range. The use of gear receiving sounds in the sonic range had earlier been abandoned because of the poor directionality and limited frequency response of hydrophones then available, the high submarine self-noise levels in the sonic frequency range, and the lack of adequate control of amplifier frequency response characteristics.

Experimentation on hydrophones for antisubmarine patrol craft had resulted in the development of toroidal and straight magnetostriction hydrophones with good wide band frequency response characteristics and with sufficient directivity to ensure noise discrimination and to determine accurately the bearing of the sound source. Tests with a hydrophone of this type showed that listening was possible at useful speeds. Development work accordingly was undertaken at the New London Laboratory, one of the first problems being to make the hydrophone uni-directional instead of bi-directional.

As ultimately developed, the JP equipment used a three-foot straight magnetostriction hydrophone mounted topside near the after-end of the forward torpedo room. The hydrophone was rotated by means of quiet hand-training mechanism and its output was amplified by means of a high gain sonic amplifier having a normally flat frequency response characteristic and incorporating a series of high pass filters. Monitoring at the amplifier was accomplished by means of headphones or a loudspeaker. Numerous patrol reports supported the evidence of extensive tests and showed that the JP

gear was reliable and accurate. Under the most favorable water conditions surface ship propeller sounds could be heard at ranges beyond 26,000 yards and the auxiliary machinery of destroyers detected up to approximately 1,000 yards. In the absence of controlling thermo-gradients the JP equipment usually gave somewhat greater range than the supersonic gear. The directionality of the JP system enabled an experienced operator to determine within approximately 1° bearings from a source, such as cavitation noise, having considerable energy in the higher sonic frequency region.

Pro-submarine Devices.

During the first two years of its existence Division 6 was able to contribute little direct assistance to our own submarines. The German U-boat menace required almost complete attention. Following the turning point in the antisubmarine war in the late spring and early summer of 1943, however, it was possible for the Division to devote an increasingly larger portion of its activities to an intensive pro-submarine program.

For some time members of the Division had had in mind many ideas concerning helpful pro-submarine devices. As the pace of the Pacific war stepped up, it became more and more important to get some of these devices into development and production. Accordingly Messrs. Shea and Glennan, as representatives of Division 6, visited the Pacific Fleet Submarine Force and with squadron and division commanders and staff officers reviewed the entire proposed program.

Already a close and profitable association had been established with ComSubDiv 41 in San Diego by the University of California's Division of War Research. Hence during 1943, as the inadequacy of our submarines' technical equipment became more and more apparent, the emphasis of UCDWR's sonar development program underwent a corresponding change in order best to serve the needs of the submarine force.

In the fall of 1943, in order to obtain first-hand information concerning the problems and needs of our submarine forces, Dr. Harnwell, Director of UCDWR, visited Pearl Harbor and conferred there with Com SubsPac, and early in 1944 other members of the UCDWR staff visited the submarine command in connection with the planning and design of various sonar devices. By the summer of 1944 some of the equipment developed by UCDWR was ready for service testing and laboratory engineers

were ordered to Pearl Harbor for temporary assignment as civilian technicians on the staff of ComSubsTrainPac. From that time forward there was an almost continuously rotating group of from one to ten UCDWR engineers assigned to the submarine force at either Pearl Harbor or Guam.

At the beginning of March 1945 the University's association with OSRD and NDRC terminated, but the contract was formally transferred by OSRD to the Navy Department and was continued under the auspices of the Bureau of Ships.

CHAPTER XIII

PERSONNEL SELECTION AND TRAINING

Importance of Special Training.

Since it is a truism that equipment is no more effective than the people who use it, the selection of Navy sonar personnel and their training in the operation and maintenance of sonar gear, constituted an important part of Division 6's program.

Training in the use of sonar equipment was particularly important for two reasons. First, there was the complexity of the gear itself. Second, in the ordinary course of service, opportunities to use the gear in actual operations were likely to be few and far between. The first reason emphasized the need for a solid grounding in sonar work; the second made it necessary to supplement initial training with periodic refresher courses.

At the outset, it was realized by both the Navy and NDRC that the quality of the Navy's echo-ranging gear was much better than the training of the operators who were to use it.

Following preliminary discussions between NDRC and the Navy, Capt. Lybrand Smith, Assistant Coordinator of Research and Development, on 3 October 1941, wrote to Dr. F. B. Jewett, Chairman of Division C, in part as follows:

"Everybody concurred in the opinion that it is desirable to study and formulate aptitude tests for personnel who are to be trained for the operation of sonic and supersonic apparatus and to formulate improved training programs for such persons. Therefore it is requested that NDRC undertake this work."

Responding to Capt. Smith's request, Dr. Jewett on 6 November recommended to NDRC acceptance of the project, and Dr. Conant wrote acceding to the Navy's request on behalf of the National Defense Research Committee.

Committee on Selection and Training.

The project, because of its scope, was assigned to Division 6 and at Dr. Tate's request, Dr. G. P. Harnwell, at that time a Technical Aide of the Division, undertook to review the problem and recommend plans for the Division's participation. Discussions with the Navy continued and out of these came a proposal for a Committee on the Selection and Training of Sound Operators, which, during its life, was to meet frequently with Navy representatives interested in various aspects of training. To this Committee, Dr. Tate in December, 1941, appointed the following: Dr. Harnwell, Chairman, Dr. Viteles, Dr. Weaver, Dr. Wilks, Dr. Fry and Mr. Shea.

An initial analysis of the problem indicated that the start of operations could best be undertaken by the San Diego Laboratory, particularly because of its close proximity to the West Coast Sound School of the Navy. Accordingly, Dr. Vern O. Knudsen, Director of the San Diego Laboratory, was authorized to employ training personnel and set up training groups. As the work of the Division in the field of selection and training expanded, training groups were established at other of its laboratories and the training activities were considerably broadened in scope. During 1942 and 1943, the major emphasis of the selection and training program had to do with anti-submarine sonar personnel, but during 1944 and early 1945, as the character of the war changed, equal or perhaps even greater emphasis was given to the training of pro-submarine personnel.

The Committee on Selection and Training served in an advisory and liaison capacity. It held regular meetings with representatives of CominCh, the Office of the Coordinator of Research and Development, the Training Commands and various Navy bureaus. At these meetings progress reports were given and new projects planned.

The training groups stationed at the Division's laboratories and at Navy facilities, were independently directed, the ultimate responsibility being the Navy's, but their efforts were coordinated through the Committee. Close contact was maintained between the various groups by frequent exchanges of personnel, by daily correspondence, and by informal reports circulated at regular intervals.

One difficulty with the Navy's training program had been that though the Navy training personnel were earnest and energetic, few members of the teaching staff had had any

teaching experience. By contrast, the selection and training groups assembled by Division 6 were composed of psychologists, educators, physicists and engineers, nearly all of whom had had special training and experience in academic or industrial selection and training work. Psychologists directed the selection research and to a large extent the general programs of training assistance to Navy activities. Physicists and engineers were responsible for the design of synthetic trainers and for assistance in maintenance instruction. Men with teaching experience in electronics were used for field work. Other teachers with less technical background were used in the writing of instruction books and in the preparation of training aids.

Selection Program.

The first meeting of the Committee on Selection and Training with representatives of the Navy was held on 4 December 1941, only three days before Pearl Harbor. At that meeting the Navy representatives explained the urgent need for the development of methods whereby better qualified students could be selected for the sound operator courses given at the West Coast Sound School at San Diego and the Fleet Sound School at Key West, Florida. Thus sonar operator selection was the top priority project. Later, the selection program was expanded to include the selection of maintenance men and still later of sonar officers.

Following the 4 December meeting, members of the committee visited both sound schools and made a preliminary analysis of the sonar operator's job. A number of standard aptitude tests were tried out experimentally on sonar operator classes entering the schools. On the basis of the results achieved, the members of the committee on 2 January 1942 were able to recommend a tentative selection scheme which was put into effect at Naval training centers in April, 1942.

Collateral research was devoted to the development of a system for the selection of sonar maintenance men. These men were chosen from the graduates of the sonar operator course and the problem was to pick the graduates who were most likely to be successful in maintenance work.

At each of the sound schools an elementary sonar maintenance course of ten weeks was given. In the summer of 1942 a study of the problem of improving selection methods for maintenance men was begun by the Division 6 training group.

In the spring of 1943, research was undertaken on the selection of sonar officers. Two studies were made but the results were not conclusive and, although a tentative selection scheme was suggested, it was never put into effect.

Training Program.

While research on selection was going on, a concurrent program was being developed looking to the improvement of the training programs at the San Diego and Key West Sound Schools.

At the time of Pearl Harbor, the West Coast Sound School at San Diego and the Fleet Sound School at Key West, combined, were turning out monthly approximately 100 sonar operators, 30 maintenance men and 20 sonar officers.

With the entry of the United States into the war, the number of sonar students was tripled, but the schools had neither the facilities nor the personnel to train men at the rate required. Due to the lack of facilities, each operator student received perhaps an hour or less of actual practice in operating sonar gear. Much of the student's time was spent in standing by waiting for a turn to operate the few pieces of training equipment which were available. Procedures and doctrines were poorly developed and completely unstandardized. It was this situation which Division 6 was asked to help correct.

Personnel to assist in the development of training methods were assigned to both schools and a section of the San Diego Laboratory was given over to the design of synthetic trainers. The work was begun early in 1942 and was carried through 1943, 1944, and into the spring of 1945.

Soon after the start of the synthetic trainer design program, primary and advanced bearing teachers had been developed and preliminary models were furnished to the schools. Shortly, additional units were being manufactured in quantity. Later, practice targets were developed to aid in training while underway. Training groups, both for sonar operators and maintenance men, were assigned to both sound schools. By the end of 1942, the two schools were graduating approximately 500 sonar operators a month; and the supply of synthetic trainers and other teaching facilities had been increased to such an extent that every student was receiving approximately 15 times as much operating experience as at the beginning of the year.

During 1943 the scope of the work of the training groups was greatly expanded necessitating the addition of a number of new members. Synthetic trainer groups, similar to that at UCDWR, were established at other Division 6 laboratories.

The training personnel at both schools at first confined their efforts to making specific suggestions for the correction of obvious defects, such as the elimination of unsupervised study and needless standby time. Later, as they became more familiar with the training problems, the Division 6 personnel worked directly with instructors in planning major revisions in course schedules. An increase in the supply of standard equipment and synthetic training devices permitted greater emphasis to be placed on operating drills and laboratory work.

One of the first problems was the measurement of student performance as contrasted with student knowledge. In the design of synthetic trainers, emphasis was placed upon designing them so that they would measure performance directly. In the case of other trainers, and for standard equipment on training ships, checking systems were devised which enabled the instructor to check and rate the student on each part of a series of complex operations. The checking systems proved not only useful for grading, but also for showing up weak spots in training.

NDRC personnel also devoted considerable time and effort to an informal program for the training of Navy instructors, though the effectiveness of instructor training was somewhat limited by the Navy system of personnel rotation. Nevertheless, members of the training group were helpful in aiding instructors in planning their lectures and drills and in coaching them in effective methods of presentation. The introduction of new equipment and of new synthetic training devices provided many opportunities to demonstrate better teaching methods.

The Division 6 training personnel produced a large quantity of training aids such as instruction books, phonograph recordings, slides and films, and wall charts. Among the most valuable training aids were phonograph recordings of underwater sound. In all, some 300 recordings were made for antisubmarine warfare sonar training. The first of these contained examples of underwater sound to be used for classroom demonstration. Then, in order to increase student participation, drill and test recordings were prepared.

Training Devices.

The development of synthetic training devices, beginning in 1942, was one of Division 6's most important contributions to the Navy's program of sonar training; but details about them may not be divulged.

The work of the training groups was not confined to the two sound schools. Work outside the schools grew to occupy an important part in sonar training. In 1943, a training representative was assigned to the Readiness Section, ComInCh, Tenth Fleet. Later, liaison men were assigned to groups also made frequent visits to other Navy training centers to assist in the installation of training equipment and to help initiate programs for the use of new synthetic trainers.

Operation of New Equipment.

From the outset it was obvious that the new devices developed by Division 6 laboratories would not be effective in service unless they were handled by operators adequately and specifically trained to use them. Thus, it became evident that representatives of the laboratories themselves would have to take an active part in instituting training programs for the service personnel who were to operate and maintain the new equipment. In order that laboratory staffs might not be burdened with the additional work of training, groups were organized at the laboratories to work specifically on training problems. It was the responsibility of these groups to plan training courses, prepare training aids and devices, and to provide the field services necessary to introduce the training courses at Navy facilities.

Practice Targets.

During the early months following Pearl Harbor, the sea phase of sonar training was seriously handicapped because every available submarine was needed in active service. Thus was created the problem of designing some sort of synthetic target.

As has been previously noted, it was very easy for sonar operators to grow rusty. They could not be spared from their

ships for refresher course ashore and it became clear that some provision must be made for shipboard training of the members of the sonar team.

Pro-Submarine Training.

By late 1943, the shift in emphasis from antisubmarine to pro-submarine warfare was reflected in the selection and training program. Only a limited amount of work was done on the selection of submarine personnel, the primary concern of the Division 6 groups being with training. In this, the NDRC training groups were able to build on their foundation of two years of experience in antisubmarine training work. Thanks to this background of experience, they were able to develop quickly a well-integrated and effective training program for submarine personnel.

At New London, a submarine training section was established. A UCDWR group aided the West Coast Sound School in the training of submarine personnel, and the Woods Hole Oceanographic Institution participated in training in the use of the bathythermograph. In 1945 when responsibility for the underwater sound program was transferred to the Navy, provision was made to continue this training assistance under direct Navy contracts.

The problem of the selection of submarine sonar operators differed considerably from that of the selection operators for antisubmarine warfare surface craft. On submarines, the sonar watches were customarily filled by assigning men of other ratings who were not occupied full time. There were no rated sonar men until 1945, and then only a few. As a consequence, the system followed in the submarine schools was to give sonar operating training to as many men as possible who might be called upon to stand sonar watches. The selection system, therefore, was in a sense a negative one. The problem was not so much to select the men best qualified to be sonar operators, but to weed out those men who might be potentially dangerous due to marked deficiencies of hearing, speech or motor coordination.

From July, 1944, to January, 1945, a group from the CUDWR laboratory was assigned to Pearl Harbor to work on selection and training problems. As a result of their efforts, a system was developed whereby men assigned to ComSubPac were classified

on the basis of their sonar ability, and entrance standards were set for all courses given by ComSubTrainPac. Thanks to the work of this group, the waste of training facilities on unqualified men was largely eliminated.

In the training of submarine personnel, profiting by the mistakes made during the antisubmarine warfare experience, the Division 6 training groups were able to follow a more orderly procedure. The development of each new training program included (1) analysis of training requirements, (2) a survey of existing facilities, (3) the planning of curricula, (4) the training of instructors, (5) the development of achievement tests, (6) the preparation of training aids, (7) the construction of synthetic trainers, and (8) field service to introduce the new program. Programs developed in accordance with this pattern were successfully carried out for sonar, voice communications and radar training.

During 1944 and early 1945, Division 6 training groups assisted in the planning and establishment of new basic courses for sonar operators at Pearl Harbor, New London and San Diego. They set up a basic maintenance course at New London and refresher courses for operators and maintenance men at Pearl Harbor, Perth and New London. Special courses were established at a number of other submarine bases.

Division 6 laboratory representatives prepared training materials and introduced courses at submarine bases in both the Atlantic and Pacific for instruction in the use of JP sonar equipment which had been developed by the CUDWR laboratory. At a later date, courses were developed for training in the use of other sonar equipment which had been developed by the Division 6 laboratories. Training material was distributed to the Naval personnel prior to the installation of equipment on the submarines, so that when the equipment finally was installed, the men, who would use it, would already have a background of information.

ComSubsLant asked Division 6 for aid in developing a training program in voice communications. To meet the request, Division 6 enlisted the aid of two other NDRC groups, the Psycho-acoustics Laboratory at Harvard University and Project N-109, the Applied Psychology Panel. The three groups collaborated in a program which involved the standardization of phraseology and procedures used in voice communications and the establishment of training courses for officers and men. The program started in April, 1944, and continued

until December. As a result of the work, a catalog of standard commands and reports, an instruction book on basic procedures, and a ship's organization chart had been prepared and issued. Instructors had been trained to give voice communication courses at advanced bases, and equipment for training rooms had been assembled and shipped to these bases.

CHAPTER XIV

FIELD ENGINEERING

Value of Field Engineering.

In wartime, when there is urgent demand for new and improved devices, it becomes necessary for the engineer to leave his laboratory and go into the field. The battlefield takes the place of the peacetime proving ground. In modern war, the advantage lies with the nation that can most quickly develop and introduce the best new and improved weapons and counter weapons. Because of the war's urgency, the periods of development and utilization must often overlap.

Equipment for fighting men whose lives may depend upon its performance must meet a dual requirement. It must be dependable and rugged enough to operate beyond normal maintenance periods. In the types of gear dealt with by Division 6, it might have to be designed to withstand the effects of pressure when submerged; or the corrosion of salt water; or the effects of tropical fungus growths; or the pounding of ship or airplane vibration; or the shock of depth charge explosions.

On the other hand, equipment must also be adaptable to manufacturing techniques common to mass production, must be capable of easy repair or replacement of parts. It must not be too difficult to operate, and not be tricky in performance. It must be designed to be readily integrated with other shipboard or airplane equipment.

The engineer and research worker have a personal as well as professional and patriotic interest in the proper design of war materiel. For the shortcomings of a single piece of new equipment may not only cause a fighting man to lose confidence in its effectiveness, but also cause him to lose confidence in researchers and the whole research program.

But the interest of the engineer does not end with design. In developing new equipment or devices, there is a complementary responsibility upon him to see that installation

is correct, that technical information for operation and maintenance is adequate, and that operation is not only satisfactory but carries out the basic ideas which lay behind the development originally. This is also true of techniques; the applications must be appropriate.

The Job of the Field Engineer.

The responsibility of getting new equipment into effective use is three-fold. The operator asks that someone help him to obtain new tools. The developer designs the tools. Between the needs of the operator and the work of the developer there is a gap which the field engineer must bridge.

In bridging the gap, the field engineer must be concerned with problems of installation, operation and maintenance. He becomes an appraiser, serves as liaison agent. He carries to the operator an appreciation of the problems of the developer; he brings back to the laboratory the operator's opinions on service requirements and operating conditions.

Finally, in wartime, the field engineer must also train personnel how to operate and maintain new devices, so that they will gain the maximum benefit from their equipment.

In the case of antisubmarine and pro-submarine warfare, operations are conducted on the threshold of an instrument's performance. Since first contact is extremely important, it is necessary to extract the last ounce of performance from the equipment.

This, of course, implies the coordination of men and equipment. Men using the equipment must operate as a team.

Men are usually trained to use equipment at the training centers. But the coordination and integration of the equipment is usually accomplished in actual service. There are many different kinds of equipment, made by different manufacturers, at different periods. It becomes the duty of a properly trained field engineer to weld this equipment into a coordinated system, and, in some cases, it is his duty to coach the men, as well, into an efficient team.

In carrying out his manifold duties, the field engineer becomes a diagnostician and a doctor. Often he is a specialist,

but to treat emergency cases, he must also be a general practitioner, with wide experience and knowledge of his subject.

Field engineers, recruited from American industry and the university laboratories, played a vital role in the antisubmarine warfare of World War II.

More Field Engineering Service Needed.

By 1943, Division 6 of NDRC had become closely integrated with Naval operations, design and research, acting as a consulting body, inventing and improving weapons and assisting in personnel training.

While a great deal was being accomplished in developing new devices for detecting, locating and destroying the enemy, it became apparent that more attention should be given to the problems of installation, operation and training in the effective use of new antisubmarine warfare weapons and devices. Also, experience showed that the performance of older types of devices often could be substantially improved. As the German U-boat threat increased, the need to bridge the gap between laboratory development and application of new devices grew more urgent.

Several Division 6 laboratories had already found that they must render field engineering service if they were to do their job right.

The research and development activities of these various groups created a problem in coordination, evaluation and use.

Field Engineering Group Proposed.

By early 1943, it became apparent that these various field engineering activities should be coordinated under one direction. Also, the Navy needed even more technical assistance in design, installation, maintenance, operation, and training methods.

If more men were sent out from the research laboratories, the research program undoubtedly would be hampered. Competent laboratory men might be wasted on field work for which they were inexperienced or unqualified.

Therefore, specially trained field engineers seemed desirable. Preliminary discussions between the NDRC and the Navy were held and it was subsequently agreed that NDRC would set up a group of civilian engineers to render field engineering service to the Navy.

Since the field engineers were to deal with design information, and the Bureaus were responsible for design in the Navy, it followed that the field engineers properly operated through and for the Bureaus on design matters. Also, since the Naval operating forces were the sole customer-users of designed equipment, the thinking of field engineers must be identified with the objectives and situations of the operating forces. For these reasons it was decided that the Group should be under the cognizance of the Bureau of Ships and that their orders and reports should be handled through Navy channels.

In keeping their civilian status, engineers would have a greater freedom of movement, freedom from time-consuming routine duties and certain other advantages not available to officers in the Navy.

On 27 April 1943, Rear Admiral E. L. Cochrane, Chief of the Bureau of Ships, issued a directive to all ships and stations announcing the formation of the Field Engineering Group by the Bureau of Ships, with the assistance of the NDRC, and with the cooperation of the Bureau of Ordnance, the Vice Chief of Naval Operations, and the Commander in Chief.

The directive was issued on 1 May 1943 as Navy Bulletin C-157 and defined the purpose, scope and mode of operation of the new Group.

Formation of the Group.

On the basis of the Navy directive, the Field Engineering Group was organized and administered by Columbia University Division of War Research, under an OSRD contract. T. E. Shea had general charge of the Group, and it was directed first by J. W. Kennard and later by Woodman Perine. The headquarters office was established in the Underwater Sound Installation and Maintenance Section of the Radio Division, Code 983, in the Bureau of Ships. The director and his assistants were located there. Business management personnel and procurement of equipment and supplies were handled by a small staff at 172 Fulton Street, New York City. Field Headquarters, including the training and information bureau, were established at the New London Laboratory of Columbia University.

Recruiting of Personnel.

The chiefs of both the Bureau of Ships and Division 6 recognized certain characteristics which field engineers should have.

These included: (1) good technical ability; (2) emotional stability and adaptability to a variety of work and conditions; (3) ability to criticize equipment constructively for operations; (4) practical ability to use tools and a "nose for trouble;" (5) eagerness and aptitude for passing on to others the knowledge and experience acquired; (6) ability to work through organization channels; (7) ability to command the confidence and respect of commanding officers; (8) resourcefulness and an ability to handle emergencies; (9) a strong sense of responsibility to people, a "feeling for service."

After a survey of the scientific and industrial fields, it appeared at first that the communications and power industries had a reserve of electronic and mechanical engineers whose industrial experience gave them the necessary "know-how" for the job. It was soon discovered, however, that the communications field had already been drawn upon heavily, so a substantial number of engineers were recruited from power companies and other sources.

Eighty-one engineers were recruited from telephone companies, radio broadcasting systems, power companies, schools and colleges, manufacturing companies, and government agencies. Their experience in these fields ranged from four to 24 years, averaging 15 years. Thus men of similar calibre but with widely specific experience and background were secured.

Training and Indoctrination.

As the men were recruited and accepted, they were sent to the New London Laboratory for training and indoctrination. The field engineer's training included: (1) a comprehensive introduction to the fields of underwater sound and anti-submarine warfare; (2) indoctrination in Navy customs and traditions, and training in the Navy's organizational structure and operating methods.

Later, training courses were broadened to cover airborne equipment and the pro-submarine warfare equipment developed

for the Pacific fleets. In conducting these courses, lectures were given by Laboratory staff members, naval officers representing the Bureaus and fleets, personnel from other research laboratories, representatives of manufacturers, and later, by experienced field engineers.

The Naval training centers made available ASW practice equipment for the trainees. The Group went on many trial operations conducted at sea and made visits to factories, naval bases and stations, and research laboratories. Some field engineers were employed for months on laboratory developments so that they could learn all the details of certain newly developed pieces of equipment. Engineers usually spent a brief period in the Bureau of Ships to learn Bureau procedures and to meet the personnel.

The period of training varied from several months to more than a year depending on the need for the engineers' services and individual capabilities.

The Manual.

An important part of training field engineers was the unique volume, "The Field Engineering Manual." For convenience, a wide variety of information on installation, maintenance and operations was collected in a single volume in order to digest essential information from Navy publications, to permit the continued study by engineers, to enable them to keep up to date on new equipment as it was released, to provide information in compact form not otherwise available, and to provide material suitable for informal or formal training of Naval personnel.

Very little material produced by others was used as originally published, and much information was developed on new devices from the ground up, and issued ahead of the manufacturers' regular instruction books. An example of this is the attack plotter guide, discussed in another section.

Field Training.

The first group of field engineers to go out under Navy orders to various Navy yards did not have the benefit of advanced field training. Subsequent groups were first assigned to work with and assist senior field engineers who had already

been on the job. It was of considerable value to all of the men to have this active and informal help in getting acquainted with actual operations in Navy yards and stations before undertaking the responsibility alone at a new activity.

Refresher and Special Training.

To insure the continuing usefulness of the Group to Naval operating forces, men were brought back from time to time to laboratories and factories to receive refresher training on equipment in the final stages of development or in production. In each case they returned to the field bringing fresh and current information on new equipment about to arrive in the fleet. Also this refresher training program made it possible for the engineers to convey a point of view gained in the field to the laboratories and factories.

Scope of Operations.

In describing the scope of operations of the Group it is impossible to include all the various functions and duties the Group performed. However the growth of the engineering activities is briefly described, followed by specific examples of work done.

When the group was formed in 1943, men were assigned - as directed by Admiral Cochrane - to the various Navy yards in the continental United States, under cognizance of the Radio Material Officer and in several cases under the Ordnance Officer, to fill the most pressing needs at that time.

Engineers were assigned to give technical assistance to RMO's making installations of sonar equipment. Having an experienced engineer from industry who had the installation, maintenance and field point of view was an advantage, since most civilian employees in the yards were not familiar with the practical shipboard use of echo ranging and sound equipment.

During this period, the field engineers made in-the-water checks of sound gear and cleared up difficulties arising from the adaptation of new devices to existing equipment. This surface-ship activity naturally evolved into certain assistance to operating bases in the continental United States.

At the operating bases, field engineers were asked to assist in tactical operations, in training facilities,

in the evaluation of equipment, and informally made modifications in operating techniques. Having had some experience in Navy yards and operating bases it was natural that engineers should begin to collaborate with laboratories and manufacturers, exchanging information on sonar and ordnance development. The engineers were developing an experience which could be used to mutual advantage in planning equipment and suggesting programs for schools and training activities. Because of the interest of the Bureau and the engineers' personal contacts, training activities and training centers accepted their assistance. The engineers could give a kind of help not readily obtainable from either officer or enlisted personnel.

In November 1943, two field engineers were requested for duty at Pearl Harbor, to assist in general sonar problems on surface ships. While working on sonar problems, they were requested to spread their services over other activities and engaged in actual installation, maintenance and consulting. As the Group grew, it served more and more in a staff capacity and as a consulting body for the various commands. New equipment was arriving at the time and the commands requested the engineers to help in training activities. As the Group became better known and the type of work it was doing was better understood, other commands such as ComDesPac and ComServPac requested engineers, and the Group continued to grow.

During the latter phases of the Group's activity, men were sent to forward bases essentially to help train Naval personnel. Previously, however, men had been sent out to do spot jobs of field engineering in the forward areas.

During and following the transition from antisubmarine warfare to pro-submarine warfare, the men assisted in pro-submarine warfare much as they assisted in antisubmarine warfare.

It may be that it would have been well to have set up the forward area coverage sooner, but perhaps this final phase of field work could only have been done after gaining the previous experience elsewhere.

As time passed, opportunities developed to serve beyond a narrow interpretation of the original Directive, and this led to such activities as distributing technical bulletins to Navy personnel, establishing formal training schools, and developing certain testing techniques which were adopted as standard procedure. Examples of these types of additional services are discussed in the next section.

As the organization grew in numbers and experience, additional assignments were made, until in the final year of operation, there was a heavy concentration of men with the forces afloat.

Field engineers served at 68 establishments and headquarters in 14 Naval districts; in eight Sea Frontiers; with four fleets and groups in the Atlantic; eight fleets in the Pacific; 16 schools and training activities; and at six laboratories.

They served at Navy yards, operating bases, Navy commands and with the forces afloat from North Africa and Europe, through the Caribbean, across the United States, through the Pacific Islands to Australia.

During a typical week, 80 engineers would be on field assignment and at least 50 of them would move during the week. At any time of the day or night, an engineer might receive orders to pack his gear, catch a plane and report within 24 hours to a base 5000 miles away. Within the United States they traveled on public transport, but most of their overseas transportation was provided by the Navy.

The men usually traveled alone or in pairs, but on one occasion it was necessary to send 15 men on one ship to Pearl Harbor.

Their casualty and sickness record was excellent. No engineer was killed on duty, and only a few were injured in accidents. This does not mean they were not exposed to risks. More than one engineer escaped death by having been luckily "bumped" from a plane that later crashed.

The need for strict security measures to protect vital information is obvious. But so far as is known no attempts were ever made to steal data, and all material issued to the men in the field was returned or accounted for when the Group was terminated.

Keeping the Engineers Informed.

From the first, it was recognized that an information service must be maintained to keep the engineers fully informed on developments affecting their work, thus assuring their value as consultants to the Navy.

Technical information was compiled from every available source, a complete library and file of instruction books were established, and the Field Manual was begun. The Information Branch was organized to provide this service and to act as a clearing house and source for assisting the engineers in the field.

Information flowed to the engineers from three principal channels: 1) the Manual; 2) "In-Between" and special bulletins; 3) correspondence and wire communications.

The Manual has been described in another section. "In-Between" was a monthly house organ which contained items of general interest, technical items, news about the work and life of the men at all stations, administrative news.

Innumerable requests for information on specific equipment or special problems confronting individual engineers were received at the New London Information Branch. Each request was answered as promptly, completely and accurately as possible. In many cases, members of the Information Office would have to get the answers from other laboratories or manufacturers.

An example will illustrate how this service operated. The field engineer assigned to the submarine base at Perth, Australia, discovered that submarines on war patrols and other operations in the Philippines area, were operating with high sound levels, making them subject to easy detection by the Japanese. At first, the field engineer not only had trouble in locating the source of the high sound levels, but he also had trouble in persuading the submarine officers to improve their boat conditions, such as rattling deck slabs, vibrating plates on superstructures, squeaky shafts, and noise due to wear and tear. The field engineer decided that he needed a sound recorder to record the boats' sound and then play it for the skippers and electronics officers.

He cabled the New London information engineer to rush a recorder to Perth. To speed delivery the information engineer cabled the field engineer at Pearl Harbor and asked him to ship his recorder to Perth and at the same time told him that a new one was being shipped from the mainland to replace the one to be shipped to Perth. The sound recorder did the job expected of it. The submarines operating out of Perth were significantly silenced.

Duties of Field Engineers.

While the problems of field engineering were complex and varied, it was possible to divide the functions of the Group into four categories: 1) giving staff assistance, 2) detection of fundamental or type equipment difficulties, 3) introduction of new equipment, 4) development of new systems and techniques of using equipment.

The engineers' contact with the fleets had revealed to them a serious and urgent need for better trained and better informed personnel. Naval operations were badly hampered during the first part of the war by lack of training facilities, inadequate technical information and inadequately trained instruction personnel. Here was another problem for the field Engineering Group.

As soon as the Group was organized, it went to work to establish better Naval training facilities. It had ships assigned to training activities and sent urgent reports to BuShips on the need of more and better training facilities.

Before the engineers could become instructors, they often had to become familiar with a whole new field of knowledge in a few days. For instance, one group of engineers took a two-hour course on how to man sound gear and fire control, and how to helm and conn the ship. The men who had been recruited proved adaptable in learning tactical as well as operational and electronic problems. They could discuss tactical and operational problems with the skipper, answer questions on operation of gear, and instruct the crew on adjusting sound range recorders and improving the accuracy of target-hitting and depth charge dropping.

In 1944, ComServPac requested the Group to help prepare a curriculum for sonar maintenance at the Pearl Harbor Radar School. This school was to train qualified radar technicians to maintain shipboard sonar equipment. Some students came from the Radar School, and others were taken from ships, trained, then returned to duty.

The school opened on November 1, 1944 and field engineers served temporarily as instructors until new instructors were available from the ASW Training Center.

Since the students who came from the ships knew what type of gear they would have to work with when they returned, it

was possible to concentrate on information of immediate use to them. The school concentrated on gear widely used by the fleet and not on new equipment -- at least not until it was installed in considerable quantity.

The sonar course proved highly effective, not only because the men could now use their ships to better advantage on war patrol, but the additional training enabled them to repair equipment casualties at sea.

Field engineers also gave underway instruction to submarine crews. At Pacific submarine bases, the engineers would go out on every submarine for one or two days instructing crews on the operation of electronic equipment.

The assistance given to staff commands was varied and extensive. Operating through the Bureau of Ships, at Navy yards and stations or with the forces afloat, field engineers: 1) modified a device for improving training facilities at the San Diego Fleet Sound School; 2) made circuit modifications and additions, and changed RCA sound gear so it could be used with a Harvard Underwater Sound Laboratory BDI on ASW training ships; 3) redesigned arrangement of sonar equipment in DE sonar huts, making the equipment more accessible and easier to maintain and operate; 4) introduced equipment and techniques of checking ship's sonar equipment on arrival or departure; 5) at the Chicago Navy Pier and the Treasure Island Training Schools, assisted with planning lay-out of equipment, procurement and installation of equipment, planned the curriculum, trained instructors; 6) planned and directed an expendable radio sonobuoy (ERSB) school for air force personnel at ASW headquarters, Oahu, and at the same time aided in solving problems of launching certain devices, designed a floating triplane radar target, and established a communications system for aircraft and ground station coordination; 7) supervised training, and development of attack techniques at the Submarine Chaser Training Center, Miami; 8) assisted in improving the use of sound equipment, repaired equipment, trained personnel on destroyer escort shakedown cruises.

Detection of Fundamental or Type Equipment Difficulties.

An important part of the field engineer's duties was to locate and diagnose equipment difficulties of recurrent character, making changes or corrections in the field, then

suggesting design changes to the manufacturer through BuShips to correct such difficulties. This work required the closest cooperation of field engineers, manufacturers, laboratories and Naval officials.

Field engineers "put out thousands of fires," soldered many connections and made other emergency adjustments, but their fundamental job was to improve equipment. If a tube burned out they would fix it, but they were more concerned with determining from circuit design why the tube burned out. They went to the crux of difficulties to determine how the manufacturer could alter or improve the design or production of equipment.

The Group's modifications of the Bearing Deviation Indicator (BDI) is a good example of detecting difficulties. The BDI was developed after echo ranging gear, and the first units were ineffective because the power transformer produced a 60 cycle hum. A field engineer discovered the hum could be reduced by relocating certain components in the equipment. His modifications were sent to BuShips and later were published in BuShips' official radio installation bulletin (RIB).

To detect fundamental equipment difficulties, a variety of experience and specialization was often necessary. For instance, one field engineer who was an experienced mechanical engineer had specialized in ASW Ordnance. He was assigned to a destroyer escort to determine why a hedgehog (Mark 10 Projector) was difficult to train under sea conditions when fully loaded. He discovered that faulty lubrication of the trunnion bearings under full load was causing an increase in friction. He suggested minor modifications in the lubricating points. His recommendations were accepted by the Bureau of Ordnance and distributed to the fleets as ordnance alterations.

Familiarity with all ASW devices was also necessary. In some cases, separate ASW devices, designed to operate integrally with other shipboard equipment did not always work as expected. For instance, one model of echo ranging gear when connected would not produce a trace on the recording paper of the range recorder to permit adjustment (no trace to zero zero). The range recorder was used for dropping depth charges and when not in proper adjustment would have range errors of 20 yards or more. A trace was needed to determine the range accurately. Field engineers detected the inadequacies, put the equipment in proper operation, and sent suggestions for modification of the

echo ranging gear to the manufacturer through BuShips. Later the Design Section and manufacturer found a way to make the necessary changes in design.

Another field engineer was able to increase the effectiveness of a harbor defense system because he could apply his knowledge of shipboard echo-ranging gear to a land defense system. The projector training system of a harbor defense equipment needed simple repairs. The field engineer assigned to clear up the trouble devised a different type of training control which he made from spare radar parts. His improvements were highly satisfactory and provided more accurate, trouble-free operation. While making the repairs, he made additional improvements to increase the effectiveness of the defense system.

Introduction and Installation of New Equipment.

As has already been seen, the field of engineers introduced many new pieces of sound gear to the fleets. The bearing deviation indicator has been mentioned. Other gear introduced included: (1) applique components for maintenance of true bearing (MTB); (2) console-type echo-ranging gear; (3) submarine sonic listening systems. In the field of ordnance, field engineers assisted in introducing the forward-firing hedgehogs and mousetraps. Also, numerous training aids were introduced.

In dealing with the early major problem of adapting and improving existing underwater sound equipment, rather than introducing complete new sound systems, field engineers converted or adapted a total of 85 types of equipment. In most cases the job was done with little or no interference with operations.

The story of two field engineers who were ordered to help install a bearing deviation indicator and maintenance of true bearing equipment on a ship at Pearl Harbor tells how engineers helped to introduce complicated devices to ASW crews. During the latter part of May, 1944, several BDI and MTB units arrived in Pearl Harbor to be installed in ASW craft. The units were checked and adjusted by the field engineers. The first ship selected for the installation of these units was one with an excellent ASW record, so every effort was made to finish the job quickly and return the ship to active duty.

The BDI units were of early manufacture and required field modification as there was no time to send them to the mainland for revision. Because the crew was unfamiliar with the equipment, arrangements had to be made so that these new units could be disconnected from the sonar gear in case of failure or damage. The field engineers furnished all the technical information and devised a system of disconnecting the equipment which the Navy Yard produced.

The two field engineers made the modifications, checked and tuned the equipment, corrected the errors, and finished the job several hours before the ship's scheduled sailing time. To do this they worked for a continuous 36 hour period. The ship's subsequent report -- a confirmed sinking of a Japanese submarine -- furnished ample reward to these men and their associates who helped to introduce this complicated equipment.

Development of New Systems and Techniques for Using Equipment.

Inevitably, field engineering work leads to the development of new systems or techniques of testing, appraising and operating equipment, instructing personnel. Even ASW tactical operations were influenced.

When field engineers were testing or inspecting shipboard equipment, or training radio technicians and sound men, they frequently found that the men did not use the sonar equipment efficiently because they did not know how to tune it properly.

The Group developed several methods of tuning echo-ranging projectors and receiver amplifiers to peak performance. They evolved empirical methods for general application of these methods to all ASW vessels. Cards as visual aids to enlisted men were developed which were suitable for easy dissemination and use in the sound rooms and these were printed in BuShips official publications. Two such cards were "How to tune a receiver," and "How to tune your QC driver." The cards were provided for shipboard coaching work and were convenient to use either lying to or underway and helped to ensure proper functioning of the equipment under any circumstances.

The importance of such a contribution may be difficult to understand. But to the field engineers who saw so many inadequacies in the life-and-death business of fighting

submarines and who observed these inadequacies in personnel as well as equipment, the widespread use of this simple method of assuring proper operation of vital equipment was extremely important.

Another kind of assistance was the development of a system of measuring the sound conditions of submarines operating at various depths and speeds. The New London Laboratory had collected data at Pearl Harbor on the noise produced by submarines as a direct result of cavitation and had made studies to link the noise with the speed and depth. As a result it was concluded that a definite relation could be established between speed and depth, and cavitation, which would vary only from boat to boat.

Field engineers assigned to ComSubPac evolved field methods of making cavitation measurements. Procedures were developed for laying out operating schedules and preparing the gear for test runs. Considerable practice was required to distinguish cavitation from other noises.

The data, or "boat signature," was compiled for each submarine tested and a chart was prepared showing the record of noise level before and after propeller cavitation at various speeds and depths. These were curves of speed versus depth showing the boundary or threshold between cavitation and the absence of cavitation. These charts were then presented to the submarine skippers.

Since propeller cavitation and other noise sources vary from time to time, particularly in war patrols when depth charges are dropped or when operating in shallow waters, this method of measurement was extremely important. Skippers were able to operate under certain conditions with at least a greater peace of mind when they had this information. Thus, field engineers even helped to improve tactical operations.

This unique cooperative effort of the men from the laboratories, factories, naval commands and forces afloat efficiently accomplished far more than anyone expected in the beginning. Because the engineers had been carefully selected and trained they were able to "grease the wheels" of ASW operations and weld the men and equipment into a single, highly efficient team. This could not have been done if all hands had not worked together. This cooperation, in summary, enabled the field engineers to:

1. Speed up the use of many new devices that played an immeasurable part in winning the antisubmarine war in two oceans.

2. Discover the facts on the inadequacies of old and new devices and report them to the men whose job was to correct and improve equipment.

3. Expedite the development of new equipment and methods by reporting the improvements urgently needed.

4. Train thousands of enlisted men and officers in schools, laboratories and in the sound rooms aboard ship.

5. Supervise the installation of new and complicated equipment on ships, submarines and planes, and improve methods of operation and maintenance.

6. Sell the men of the fleets on the kind of work done by research organizations and field men, and thus win the personnel's confidence and understanding of the purpose and usefulness of new devices.

From the beginning, the field engineers knew that the Group's life would extend no longer than the period of emergency, and if the work were to be continued, someone else would have to be trained to carry on. Whenever they fixed up a situation, before they turned to another job, they always trained Navy personnel to carry on.

Early in the spring of 1944, the Navy proposed that an organization within the uniformed Navy be developed as a permanent solution to the problem of making specialized engineering talent available. A subordinate command at the Naval Research Laboratory founded such an organization of officer-engineers to serve as an installation, maintenance and operation group.

During the last year, the Field Engineering Group trained 30 specially selected Navy sonar officers to form the nucleus of the Navy's permanent field engineering group. Today, the Sonar Section of the Electronic Field Service Group, operating under the Naval Research Laboratory, closely corresponds with the wartime Field Engineering Group. Thus, the work of field engineering goes on in peacetime.

There are good reasons for the continuation, since both in the armed services and in industry, there will always be

the problem of coordinating the manufacture, installation, maintenance and training in the effective use of newly developed instruments of warfare.

The Future.

If the nation ever faces another emergency like the one in 1941, how could field engineering be improved?

The men who worked so closely with the Group at headquarters and in the field have had many suggestions. But it appears that most of the difficulties the Group encountered in doing its job can be traced to its late start. When the organization was formed, the crisis was at its peak and there was no time for refinements. If there is another emergency, such a group undoubtedly should be formed, trained and put to work as quickly as possible. Since the Navy now has a permanent field engineering group within its ranks, it should be easier in the future to expand and train additional personnel more quickly.

This raises the question of whether the armed services should again recruit civilian engineers for integration with the forces. This question cannot be answered here. But the success of the Field Engineering Group should indicate that there will always be a place for civilian assistance.

GLOSSARY

AAFAC - Army Air Force Antisubmarine Command.
AirAsDevLant - Aircraft Antisubmarine Development Detachment, Atlantic Fleet.
ADP - Ammonium dihydrogen phosphate.
AS/ or A/S - Anti-submarine
AsDevLant - Antisubmarine Development Detachment, Atlantic Fleet.
ASDIC - Anti-submarine Detection Investigating Committee; British sonar gear.
ASW - Anti-submarine Warfare.
ASWIS - Anti-submarine Warfare Instructors' School.
ASWORG - Anti-submarine Warfare Operations Research Group.
ATF - Automatic Target Follower.
BDI - Bearing Deviation Indicator.
BuShips - Bureau of Ships, Navy Department.
CAM - Merchant vessel equipped with catapult-launched plane.
CNO - Chief of Naval Operations.
CominCh - Commander-in-Chief, United States Fleet.
ComServPac - Commander, Service Force, Pacific Fleet.
ComSubDiv (No.) - Commander, Submarine Division (No.).
ComSubsPac - Commander, Submarine Force, Pacific Fleet.
ComSubsTrainPac - Commander, Submarine Training Force, Pacific Fleet.
CRO - Cathode ray oscillograph.
CUDWR - Columbia University Division of War Research.
DCI - Depth charge intervalometer.
DE - Destroyer escort.
ERSB - Expendable radio sonobuoy.
"Hedgehop" - Multiple spigot Antisubmarine Mortar for Surface Vessels.
H/F D/F or "Huff Duff" - High Frequency Direction Finder.
HUSL - Harvard Underwater Sound Laboratory.
JK - Underwater Sound Listening System Using Crystal Microphone.
JP - A type of sonic listening system for submarines.
MTB - Maintenance of True Bearing.
MV - Multi-spot Listening System.
NM - Type of echo-ranging magnetostriction projector.
NRL - Naval Research Laboratory.
OAY - Self-noise measuring equipment used on submarines.
ORG - Operations Research Group.
PPI - Plan Position Indicator.
QA - Echo-ranging gear with quartz crystal projector (British).
QB - Echo-ranging gear with Rochelle salt projector.
QC - Echo-ranging gear with magnetostriction projector.

RIB - Radio Installation Bulletin.
SADU - Sea-Search Attack and Development Unit.
S-band Radar - Microwave (10-cm.) radar.
SCR - Search radar.
SGM - Sound gear monitor.
SJ - Submarine radar.
UCDWR - University of California Division of War Research.
USRL - Underwater Sound Reference Laboratories, Columbia University.
VLR - Very-long-range antisubmarine aircraft.
WHOI - Woods Hole Oceanographic Institution.
X-band Radar - Microwave (3-cm.) Radar.

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